AFWL-TN-84-14

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SNAP REACTOR OVERVIEW

Susan S. Voss

August 1984

Final Report

Approved for public release; distribution unlimited.

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This final report was prepared by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, under Job Order 57972301. Susan S. Voss (NTYN) was the Laboratory Project Officer-in-Charge.

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UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): AFWL-TN-84-14

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: Air Force Weapons Laboratory

6b. OFFICE SYMBOL (If applicable): NTYN

7a. NAME OF MONITORING ORGANIZATION:

6c. ADDRESS (City, State and ZIP Code): Kirtland Air Force Base, NM 87117

7b. ADDRESS (City, State and ZIP Code):

8a. NAME OF FUNDING/SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c. ADDRESS (City, State and ZIP Code):

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62601F	5797	23	01

11. TITLE (Include Security Classification): SNAP REACTOR OVERVIEW

12. PERSONAL AUTHOR(S): Voss, Susan S.

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM 82 Jun TO 83 Dec

14. DATE OF REPORT (Yr., Mo., Day): 1984 August

15. PAGE COUNT: 104

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.
18	14	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): SNAP, SNAP 10A, SNAP 2, SNAP 8, SNAP 50, Space Reactor, Zirconium-Hydride, SNAPSHOT, SNAP Reactor, SNAP Experimental Reactor, SNAP 2 Developmental Reactor, SNAP 8 (Over)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The SNAP reactor programs are outlined in this report. A summary of the program is included along with a technical outline of the SER, S2DR, SNAP 10A/SNAPSHOT, S8ER, and S8DR reactor systems. Specifications of the designs, the design logic and a conclusion outlining some of the program weaknesses are given.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Susan S. Voss

22b. TELEPHONE NUMBER (Include Area Code): (505) 844-0146

22c. OFFICE SYMBOL: NTYN

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

18. SUBJECT TERMS (Continued)

Experimental Reactor, SNAP 8 Developmental Reactor, SNAP 50/SPUR, SPUR.

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I. INTRODUCTION

The Space Nuclear Auxiliary Power (SNAP) program was begun in 1955 and terminated in 1973. During that period approximately $850 million *then-year* dollars were spent to develop nuclear power sources capable of producing from 500 W up to 1000 kWe. The technology base was broad and encompassed a wide range of materials and power conversion systems.

This report gives a concise description of the overall space reactor program with emphasis on the main SNAP reactors and a detailed account of their design and testing. This report is not meant to be a detailed review of the technical accomplishments, but rather a starting place to present an overall picture of the program.

II. SPACE REACTOR PROGRAM REVIEW

ZIRCONIUM-HYDRIDE (Zr-H) SPACE REACTOR HISTORICAL OVERVIEW

In 1948, the Air Force (AF) commissioned the Rand Corporation to recommend development work in reconnaissance satellite programs known as Project Feedback (Ref. 1). The growing need for a reliable power source for space applications was addressed. Specialized studies on nuclear-electric sources for space applications were done under the Pied Piper Program conducted in 1954 (Ref. 2). These studies were later integrated into the Weapons Systems 117-L (WS 117-L) program, which conducted studies on a wide spectrum of energy and satellite systems for space. From 1952 to 1955 the Atomic Energy Commission (AEC)* did an analysis of nuclear power sources and evaluated them on their feasibility to be used with future spacecraft. In 1955, a joint AF-AEC committee established specifications for nuclear power in space. This included the power, life and interrelation of the nuclear device and spacecraft. The role of the AEC was to promote the development and utilization of atomic energy. The Pied Piper Program was later renamed the SNAP program.

The objective of the AEC's SNAP Program was development of compact, lightweight, reliable atomic electric devices for space, sea and land uses. The AEC was a procurement agency for Department of Defense (DOD) and National Aeronautics and Space Administration (NASA) requirements. It was responsible for developing technology that would allow the requirement to be generated as well as for meeting that requirement and for carrying out the initial phases of the test operation. The AF was in charge of establishing a mission and providing support in the launch phase (Ref. 1).

In 1955, a formal request for proposal studies was issued jointly by the Department of Reactor Development (DRD) of the AEC and the Air Force Wright Air Development Center (AFWADC). AiResearch and Atomics International (AI) proposed a Zr-H reactor coupled to a Mercury-Rankine power conversion system. The early work was done independently by Lockheed Missiles and Space Division (LMSD) with Thompson Ramo Wooldridge (TRW) and AI with AiResearch of the Garrett Corporation. Funding was jointly sponsored by the AEC for the reactor development and the AF for work on the power conversion system (Ref. 3).

*Now known as Department of Energy (DOE).

The request was specifically for possible power sources (1 to 10 kWe) with minimum weight and the ability to operate for up to 1 year of unattended operation. The acronym SNAP initially stood for Secondary Nuclear Auxiliary Power was later changed to Systems for Nuclear Auxiliary Power. The even numbered SNAP were for the reactor systems and the odd numbered for the radioisotope generator (RTG) systems.

In June 1957, AEC assumed complete control of the project and AI became the prime contractor. TRW was contracted to complete work on the power conversion system and the research being completed by AiResearch was phased out completely by March 1958 (Ref. 3). Atomics International chose an epithermal reactor design for space applications over a fast reactor because the critical mass of a useful fast reactor would result in an uranium cost of the order of one million dollars (1961). For a reactor which was to be produced in quantity the resulting cost would have been greater than that of delivery into space when the launch costs fell below $1000 per pound (Ref. 4). Also, for temperatures between 315 to 1093°C the Zr-H reactor was lighter than an equivalent fast reactor.

The early space reactor system was considered to be essential in meeting near-term and future power needs in space. The Joint Committee on Atomic Energy (JCAE) urged that an aggressive program be pursued and that it should be given high priority by both NASA and AEC (Ref. 1).

The first SNAP critical assembly was tested in October 1957, three weeks after Sputnik I was launched. The SNAP Experimental Reactor (SER) was operated in 1959 and the SNAP 2 Developmental Reactor (S2DR) in 1961. The SNAP 2 reactor had Zr-H fuel to be coupled with a Mercury-Rankine power conversion system. Table 1 is a compilation of SNAP reactor test experience and Table 2 outlines the development program.

In December 1963, the SNAP 2 program was cancelled due to government budget cuts. The Mercury-Rankine program managed by TRW was also phased out beginning October 1, 1966. Funding for the SNAP 2 reactor including CRU through Fiscal 1964 totalled $60 million (Ref. 5).

In 1958, the AF requested AI to study a reactor designed with thermoelectric conversion units. In March 1959, the AF established a firm requirement for a 500 W unit when the SNAP 10A program was started for use with a

TABLE 1. SNAP REACTOR TEST EXPERIENCE (after Ref. 6).

	SNAP 2 Experimental Reactor (SER)	SNAP 2 Developmental Reactor (SDR)	SNAP 8 Experimental Reactor (S8ER)	SNAP 10A Flight System (FS-3)	SNAP 10A Flight System (FS-4)	SNAP 8 Developmental Reactor (S8DR)
Critical	September 1959	April 1961	May 1963	January 1965	April 1965	June 1968
Shutdown	December 1960	December 1962	April 1965	March 1966	May 1965	December 1969
Thermal power	50 kwt	65 kwt	600 kwt	38 kwt	43 kwt	600/1000 kwt
Thermal energy	225,000 kwt-hr	273,000 kwt-hr	5.1×10^{6} kwt-hr	382,944 kwt-hr	41,000 kwt-hr	4.3×10^{6} kwt-hr
Electric power	-	-	-	402 watts	560 watts	-
Electric energy	-	-	-	4028 kw-hr	574 kw-hr	-
Time at power & temperature	1800 hr AT 648°C 3500 hr ABOVE 482°C	2800 hr AT 648°C 7700 hr ABOVE 482°C	1 yr AT 704°C 400-600 kwt	10,005 hr (417 days)	43 days	7500 hr

TABLE 2. SNAP REACTOR SYSTEM DEVELOPMENT PROGRAMS (after Ref. 6)

	SNAP 10A	SNAP 2	NASA SNAP 8	SPUR SNAP 50
Power (kwe)	0.5	5	35 to 50	350
Reactor Power (kwt)	30	55	600	2500
Efficiency (%)	1.6	9	8	14
Reactor Outlet Temperature (°F)	1000	1200	1300	+2000
Reactor	$U-ZrH_x$ Thermal	$U-ZrH_x$ Thermal	$U-ZrH_x$ Thermal	UC Fast
Primary Coolant	NaK-78	NaK-78	NaK-78	Lithium
Power Conversion	Ge-Si Thermoelectric	Hg Rankine	Hg Rankine	K Rankine
Boiling Temperature (°F)	-	930	1070	-
Turbine Inlet Temperature (°F)	-	1150	1250	1950
Condensing Temperature (°F)	-	600	700	1300 to 1400
Hot Junction Temperature (°F)	930	-	-	-
Cold Junction Temperature (°F)	615	-	-	-
Radiator Temperature (°F)	615	600	580	1300 to 1400
Radiator Area (ft^2)	62.5	120	1800	700
(ft^2/kwe)	125	40	45	2
System Unshielded Weight (lb)	650	1200	10,000	6000 (EST)
(lb/kwe)	1300	240	300	10 to 20
Available	1965		1972	
Development Agency	AEC	AEC	AEC/NASA	AEC/AF
Flight Test Agency	AEC(AF)	*	*	*
System Contractor	Atomics International	Atomics International	Aerojet General	Pratt & Whitney
Power Conversion Contractor	Radio Corp of America	Thompson Ramo Wooldridge	Aerojet General	AiResearch
Reactor Contractor	Atomics International	Atomics International	Atomics International	Pratt & Whitney
Flight Test Contractor	Lockheed			
Status	Complete	Cancelled	Continuing	Cancelled

*Flight Test Plans Undefined.

reconnaissance satellite. In March 1960, Westinghouse Electric Corporation was awarded a contract to develop a thermoelectric converter to be used with a space reactor. The initial SNAP 10 design was a purely conduction cooled system (Fig. 1) which was later changed to include a forced convection heat transfer system.

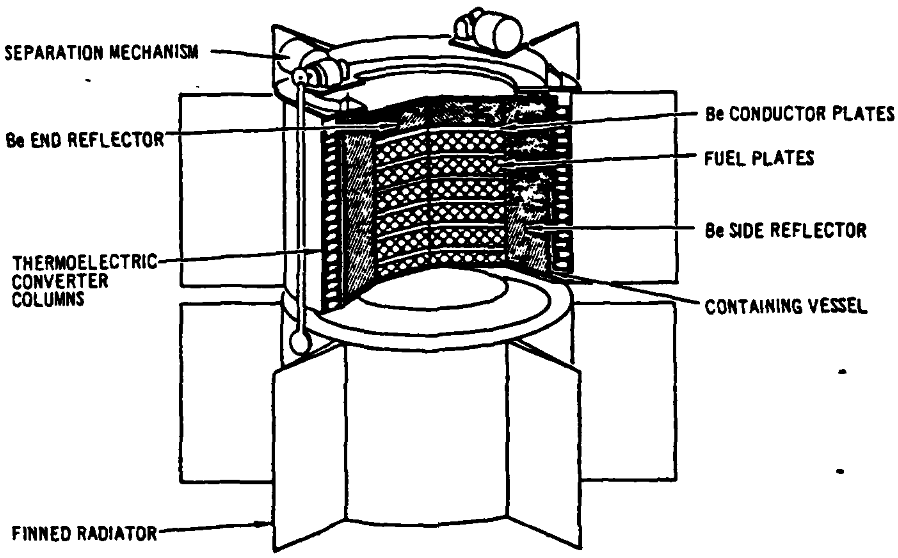

Figure 1. Original SNAP 10 concept (after Ref. 7).

In May 1960, the AEC and AF jointly initiated the Space System Abbreviated Development Plan for Nuclear Auxiliary Power Orbital Test (SNAPSHOT) program. A total of four flights were scheduled; two SNAP 10 launches and two SNAP 2 launches. The LMSD was designated as the AF prime contractor responsible for the launch vehicle, system integration and launch operation and AI as AEC prime contractor for reactor power unit development (Ref. 8).

In 1963, changes in the AF program resulted in the cancellation of a specific requirement for the 0.5 to 3 kWe power range. The most advanced program for use with the nuclear power supply was Project 461 which had experienced setbacks due to technology and budget cuts and, therefore, was no longer considered a valid candidate (Ref. 1). The AF experienced a major cut in their FY 64 budget which called for a reorganization of priorities. This reorganization also called for a change in the AEC program.

The rate of development for particular reactor systems designed for specific flight missions were slowed in keeping with the requirements of the user agencies. These changes included the cancellation of the SNAP 2 reactor, but with continued development of its power conversion system, cancellation of the SNAP 4 reactor and cancellation of the SNAP 10A flight test. The flight test was cancelled because there was no immediate requirement existing for the flight unit and according to AF policy there was to be no flight test unless there was a requirement for operational needs (Ref. 9).

These changes were of major concern to the JCAE. They coordinated meetings between AEC, AF, AI and LMSD to better understand the chain of events (Ref. 9). It was agreed by all agencies that the flight test was needed to provide the user with a sense of confidence in the power source. The AF had requested that the flight be funded but DOD disagreed because they felt it was the primary responsibility of the AEC since potential applications for the project had been delayed. The AEC had appropriated the money in the FY 65 budget but it was denied by the Bureau of the Budget (Ref. 9).

The AEC requested $15 million to flight test the SNAP 10A, but the Bureau of the Budget* turned down their request and reduced the sum to $8.6 million. Funding for the SNAP 10A totalled $53 million dollars through FY 64. The objective of the reoriented development was to push the output from the hundreds of watts into the kilowatt and megawatt range (Ref. 5).

Members of the JCAE conducted an aggressive approach in finding monies for the launch. The AF consented to continue financing the launch through their prime contractor LMSD and to use AF personnel to assist in management, contract administration and launch operations (Ref. 9).

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*Now known as Office of Management and Budget (OMB).

In February 1964, the Joint Congressional Committee on Atomic Energy proposed that the AEC fund the SNAP 10A flight test. A total of $14.6 million dollars was approved for the controversial flight test (Ref. 9). The SNAP 10A was reinstated on March 1964 with the actual flight test on April 3, 1965. The system functioned properly for 43 days until the voltage regulator sent spurious commands, causing premature shutdown of the reactor. The SNAP 10A program was formally concluded on June 30, 1966.

In 1959, NASA requested a power source in the 30 kWe and up power range for electric propulsion and interplanetary communication. This was the beginning of the joint NASA and AEC development of the SNAP 8 reactor. It was to be a minimum of a 5-year joint effort between both agencies. NASA was in charge of developing the power conversion equipment and overall system integration while AEC was to develop the reactor (Ref. 1). Aerojet-General Corporation was NASA's prime contractor while AEC continued with AI.

It was designed to produce 30 to 60 kWe for up to 1 year using a Mercury-Rankine cycle power conversion system. Two systems were tested under the SNAP 8 program: the SNAP 8 Experimental Reactor (S8ER) and the SNAP 8 Developmental Reactor (S8DR). Cracked fuel cladding was found upon posttest examination in both systems.

After the SNAP 8 program was concluded, studies were continued using the basic SNAP reactor with minor adjustments. These include the 5 kWe Reactor Thermoelectric System and the Advanced Zirconium-Hydride Reactor. There were alternate programs being pursued at the same time as the SNAP reactor program, many of these began when the Airplane Nuclear Propulsion (ANP) program ended in 1961. It was continued with a technology development program at General Electric (GE), Pratt and Whitney, Oak Ridge National Lab (ORNL) and Los Alamos Scientific Lab (LASL)*. The GE effort was continued in the design of the 710 reactor system. Pratt and Whitney continued with their design of the SNAP 50 and ORNL with their work on the Medium Power Reactor Experiment (MPRE) (Ref. 10). These were later designated the advanced power reactors which were being developed to meet power needs from the upper kilowatt-electric range to the megawatt range.

*Now known as Los Alamos National Laboratory (LANL).

The SNAP program was ended in the early 1970s due to cutbacks in government funding. It was during this time that many concurrent space programs also experienced cutbacks or were ended as government spending was shifted away from space exploration and development work. In 1971, major changes were being made within the engineering industry. Both manned and unmanned programs were severely curtailed as the Nixon Administration refused to commit itself to a firm post-Apollo plan because of social and economic problems. NASA was forced to reorganize its priorities, which included reducing or omitting programs so that emphasis could be placed on the development of the space shuttle and the national space station.

During 1969 NASA came up with a requirement which would need the Zr-H reactor system which was the semipermanent orbiting space station. This helped the Zr-H system weather through the major FY 71 budget cuts. It was considered important for future space base programs for NASA and essential to an evolving space base program. The Zr-H was changed to include a life expectancy of 20,000 h and possible 4-π shielding designs for use with manned missions (Ref. 11). The advance liquid metal program was cancelled and General Atomics (GA) was chosen as the prime contractor for thermionic development. A thermionic reactor was continued to be supported because of its potential to meet a variety of power needs (Ref. 12).

The FY 71 budget cuts did result in a 75 percent decrease in funding for the Zr-H system, 30 percent decrease in the thermionic studies, 50 percent decrease in reactor safety, termination of the Brayton cycle power conversion by NASA and the reduction of the NERVA rocket program to fuel development. These reductions were to permit allocation of funding to higher priority programs (Ref. 12).

The Zr-H reactor program once again was reoriented in 1972 by focusing on a 5 kWe system using a thermoelectric conversion system with a lifetime of 5 years. The program was to be accelerated if a mission was identified. Also, during this time NASA's emphasis changed as work on the space shuttle begin (Ref. 13).

In 1973, NASA and AEC closed out on the entire program for the development and application of nuclear reactor power in space. The emphasis was shifted to RTGs which could meet the power needs for DOD's and NASA's near term missions. David Gabriel, the Director of Space Nuclear Systems Division of the AEC concluded in his statement to the JCAE that "... the missions which were likely to require large amounts of energy, now appear to be postponed until around 1990 or later. These projected delays along with budget priorities, led to the decision that the distant payoffs did not warrant continued funding of high powered nuclear propulsion and reactor power systems" (Ref. 14).

The space reactor program was on a sharp decline since 1964 when the AEC was forced to recognize that a mission requirement was needed to continue development. At this point the emphasis was shifted away from flight missions to a long-term development program. A definite and urgent mission would have been needed to shift the program's momentum back to a viable system.

A low level of funding was continued on the space reactor program. This included work on thermionic conversion and thermoelectric conversion systems.

During FY 73, NASA spent $6.7 million on space power and reduced spending to one million during FY 74 (Ref. 5). Fiscal 1974 budget for research and development of NASA totalled $2.2 billion.

SNAP 50 PROGRAM REVIEW

The SNAP 50/SPUR program was established under a triagency agreement between AEC, NASA and the AF in 1962. The SPUR was an acronym for Space Nuclear Unit Reactor. It was separate from the space power work being conducted at AI. The SNAP 50 was a fast reactor with a predicted output of 300 kWe which could be upgraded to 1000 kWe. It was to have an operating lifetime of 10,000 h with a minimum specific weight of 20 lb/kWe, not including shielding.

The AEC was responsible for the overall coordination of a prototype demonstration power plant through flight test. The AF was responsible for establishing a requirement, project integration and flight testing while NASA maintained cognizance of the program and contributed appropriate technical data from its other related work.* Pratt and Whitney was assigned to develop

*Speech by Dr. R. I. Strough, CANEL, Pratt-Whitney, 1964.

the reactor, shield, auxiliary pump and control system. They were also in charge of the overall integration of the power plant design and development. AiResearch was selected to design and develop the boiler, condenser, and turboalternator. The reflector drive-motor was to be developed by Westinghouse Electric Corporation.

Pratt and Whitney was chosen as the main contractor due to the work they had just completed on reactor power systems. From 1956 to 1961, they conducted studies for the ANP program. This included the technological development to construct and operate a compact, high temperature, lithium-cooled reactor. Studies were also conducted by Pratt and Whitney on a sodium cooled, solid-fuel element reactor. Emphasis was later shifted to work on the Lithium Cooled Reactor Experiment (LCRE) which operated at 1903°C with a power output of 10 MWe.

In November 1962, a triagency agreement was signed authorizing Pratt and Whitney to begin work on a space reactor system. Work on the SNAP 50/SPUR was completed at the Connecticut Advanced Nuclear Engineering Laboratory (CANEL), Middleton, Connecticut. The Army Corps of Engineers constructed CANEL in 1957. A total of 1600 Pratt and Whitney employees worked on the project and 14 full-time employees from the AEC.* The SNAP 50 had a budget of approximately $20 million per year for work on system development and material testing. By 1965, the component designs, materials, fuels and subcomponent development phase had been completed. Pratt and Whitney submitted a proposal for continued work which would enable them to prepare a qualified system to be flight-tested in the early part of 1975 after completion of reactor and electric conversion system ground testing.

The estimated cost to carry the program through ground testing of a prototype SNAP 50 was estimated to be $500 million and double that for a flight qualified unit. A power plant for manned space flight would cost several billion dollars, since extensive flight testing would be needed to meet the stringent reliability requirements (Ref. 15). Funding was denied due to a lack of a specific application for a high power system in space, also the AEC did not envision the construction of a reactor experiment or of a prototype

*CANEL Press Kit, Pratt-Whitney, 1962.

system for sometime. Instead they closed the program at the point of technology and materials development. The program was rapidly shutdown with the initiation of government budget cuts. In 1965, the Congressional AEC strongly recommended to AEC that it shift the SNAP 50 program out of CANEL due to major changes in the programs objectives (Ref. 16). Although the program did not proceed past the developmental stage, Pratt and Whitney were commended by the Chairman of the AEC, Dr. Glenn Seaborg, for a well managed program which had met its objectives (Ref. 17).

In 1967 work on advanced space power systems was transferred to the Lawrence Radiation Laboratory (LRL), Livermore, California. The SNAP 50 technology was used as a basis for initating the LRL program (Ref. 18). Several reference designs were generated by LRL to help in determining problem areas and performance capabilities.

The designs represented several classifications of space reactors, from near-term to advanced technology. The designs included detailed paper and computer studies on materials and system analysis (the systems were never tested).

In 1968 the LRL-710 program was closed out to put emphasis on the SNAP 50 and thermionic reactor which were considered to have a wider range of application. Also, the funding for the SNAP 50 was reduced at this time with its pace dependent upon future needs and progress. The AEC work on the Mercury-Rankine was ended, but NASA continued with their development of the project.

Through the early 1970s, NASA Lewis Research Center incorporated the SNAP 50/SPUR design research in developing the Advanced Power Reactor (APR). The APR was an uranium nitride fueled, fast spectrum reactor. It was designed to operate at 2.17 MWt with a nominal power output of 300 kWe. The design operating lifetime of the reactor and power plant was set at 50,000 h (Refs. 19 and 20).

The reactor design had 253 fuel pins. The fuel was fully enriched uranium nitride clad in tungsten and T-111 (Ta 8% W, 2% Hf) and then placed in a T-111 honeycomb structure. The core heat was removed by lithium which flowed through an annular passage between the honeycomb structure and fuel pin.

The core was reflected by a layer of TZM (Mo - 0.5% Ti, 0.08% Zr) which surrounded the core vessel. Within the outer reflector were six control drums. The control drums contained fuel pins on one side of the drum and T-111, which acted as a poison, on the other side. Reactivity was gained by rotating the fuel into the core.

The APR was to use a Brayton power conversion system. The design included a single, lithium cooled primary loop, one or more complete inert gas power conversion loops, and a main radiation loop for waste heat rejection (Refs. 1 and 20).

Although the system was never tested, research was completed on materials, power conversion, and shielding. The APR reports bring together much of the technology from the SNAP program in a coordinated fashion. This information could prove valuable to the present space power program.

SPACE REACTOR SAFETY

The apparent need for a safety program led to the inception of the Aerospace Nuclear Safety Program. The program was established to evaluate the nuclear hazards associated with the construction, launch, operation and disposal of SNAP systems and to develop methods and designs to assure their radiological safety (Ref. 21).

The safety structure was predetermined by interactions between AEC, AI, Sandia National Laboratory, AF, NASA and other participating agencies. In this manner a safety plan was defined in the early 1960s. Atomics International had primary responsibility for safety and was funded by the AEC. Other associate contracts were also funded by the AEC. Laboratories such as Sandia and Phillips Petroleum were chosen for specific tests because of their facilities.*

The philosophy behind the safety tests was to view the tests as a means of confirmation of an analytical model. Many of the tests provided comparison of the physical phenomena to the analytic tools as a means of modeling the system. The excursion tests that were done at Idaho National Laboratory by Phillips Petroleum were important in supporting the analytical predictions and as a means of verifying how safe the system actually was.

*Personal conversation with Bob Detterman of Rockwell Int., September 15, 1961.

The tests were designed by the contractor with feedback from governing agencies. Many times special instrumentation was needed in which the contractor could go outside of his/her own organization to seek support, if it had the approval of the AEC. Atomics International would then provide the reactor hardware for the test. Sandia National Laboratories was AEC's main contractor for the Aerospace Safety Independent Review. They conducted many of the major tests and evaluated the results. Before a launch was permitted AI had to provide proof that under all circumstances the launch of the reactor would not pose a serious threat. First they had to go before an AEC licensing board which was the advisory committee on safeguards used for civilian nuclear plants. The safety committee had planned to adopt the same stringent safety review used for civilian purposes with the exception of the public review. All review was done in a closed meeting. Upon receiving approval of the safeguards board they had to receive final approval by a joint committee of AF and AEC.

Experimental and analytical work was done on reactor disintegration, fuel rod reentry burnup, critical configurations, reactor transient behavior, mechanical and thermochemical incidents, end-of-life shutdown and disposal mode shutdown. The test results provided a firm basis for the evaluation of the probability of potential radiological exposure for particular SNAP missions.

The results of the Aerospace Safety Program are most applicable to the SNAP 8 and SNAP 10A reactor, but many of the results can be applied to current programs. These include the analytical models developed in the areas of reentry trajectory and stability, heat transfer and fluid flow, and flow dependent chemical reactions. Also, much data on the thermophysical, thermochemical and mechanical properties of fuel, structure and shield materials are applicable to the current program (Ref. 21). Also, the logic and structure behind the SNAP safety tests can be evaluated and applied to the current safety program.

III. SNAP 2 POWER CONVERSION PLANT

The SNAP 2 system was designed as a self-contained auxiliary power unit capable of producing 3 to 5 kWe. In the system, sodium-potassium (NaK) is circulated through the reactor core and then flows into the boiler-superheater where the heat is transferred to the mercury working fluid of the Rankine power conversion cycle (Fig. 2). The mercury becomes superheated vapor which is expanded through the turbine. The turbine's mechanical output is converted into electrical power by an alternator. The mercury vapor is then condensed in the radiator-condensor to complete the cycle (Fig. 3). The Power Conversion System (PCS) has all of its rotating components mounted into a single shaft unit called the Combined Rotating Unit (CRU). The design philosophy behind the S2DR flight system was one of dependability at minimum weight which could survive launch stresses and temperatures.

The CRU was developed by TRW, Inc. The design criteria for the CRU turboalternator are as follows:

- Net power output of 3.5 kWe
- Isothermal, hermetically sealed housing
- Mercury lubricated bearings
- Permanent-magnet (PM) alternator
- Single shaft assembly
- Vapor cooling of alternator

Mercury vapor entering at a temperature of 621°C, and a pressure of 8 kg/cm^2, expands through the two stage axial-flow turbine which drives the three-phase, six-pole PM alternator. The shaft of the unit rotates at 36,000 rpm. The mercury vapor exhausts to a pressure of 0.6 kg/cm^2 and cools the alternator as it flows through the unit and over the finned stator housing. The shaft is supported by two mercury-lubricated journal bearings for which lubricant is supplied by the on-shaft centrifugal mercury pump. The enclosure housing is hermetically sealed, as is the alternator stator (Ref. 3).

The final design was the CRU-V. An accumulated time of 21,196 h of testing was completed on the flight-type CRU-Vs. The conclusions drawn were:

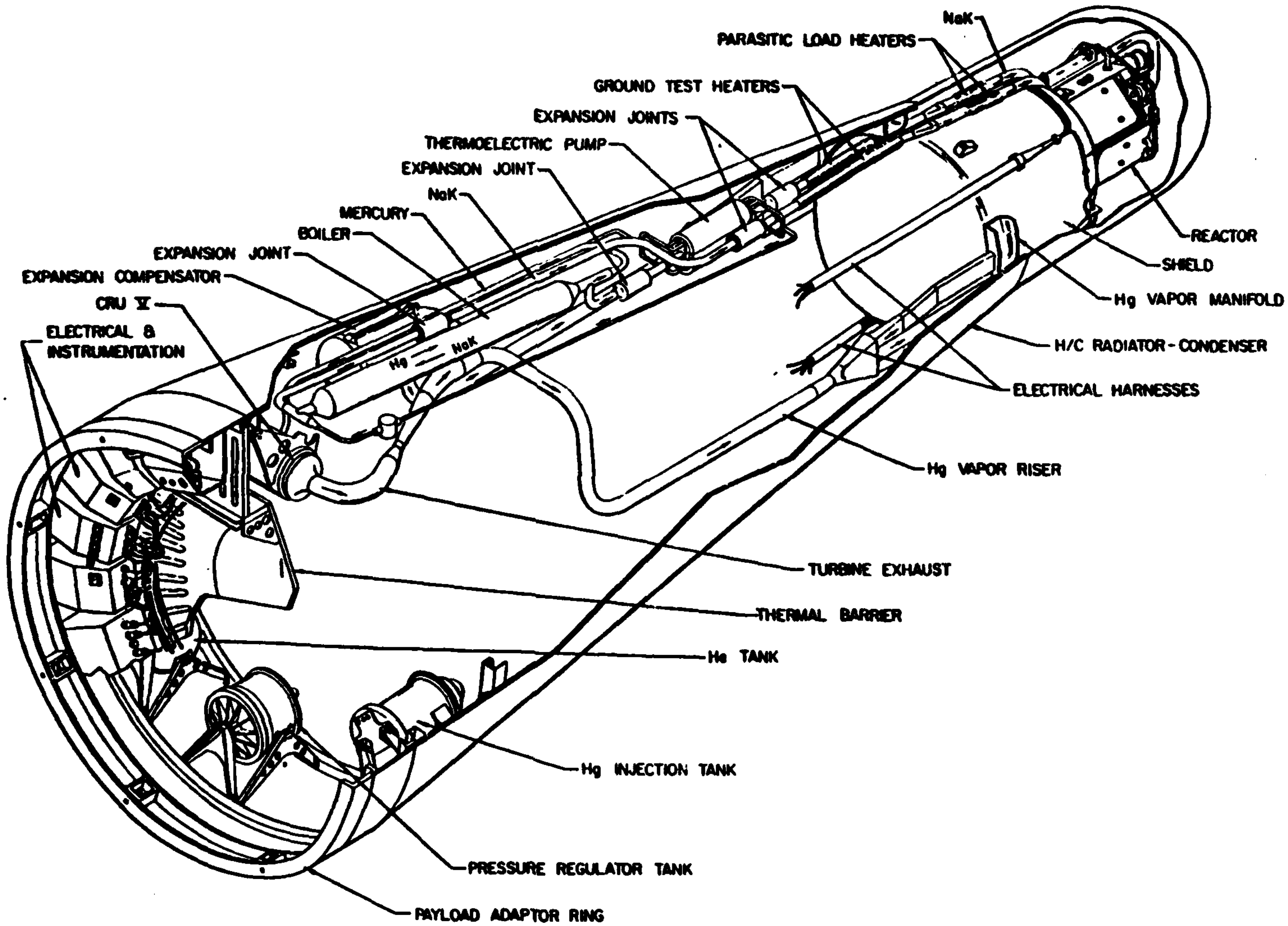

Figure 2. Structural illustration of SNAP 2 unit (after Ref. 22).

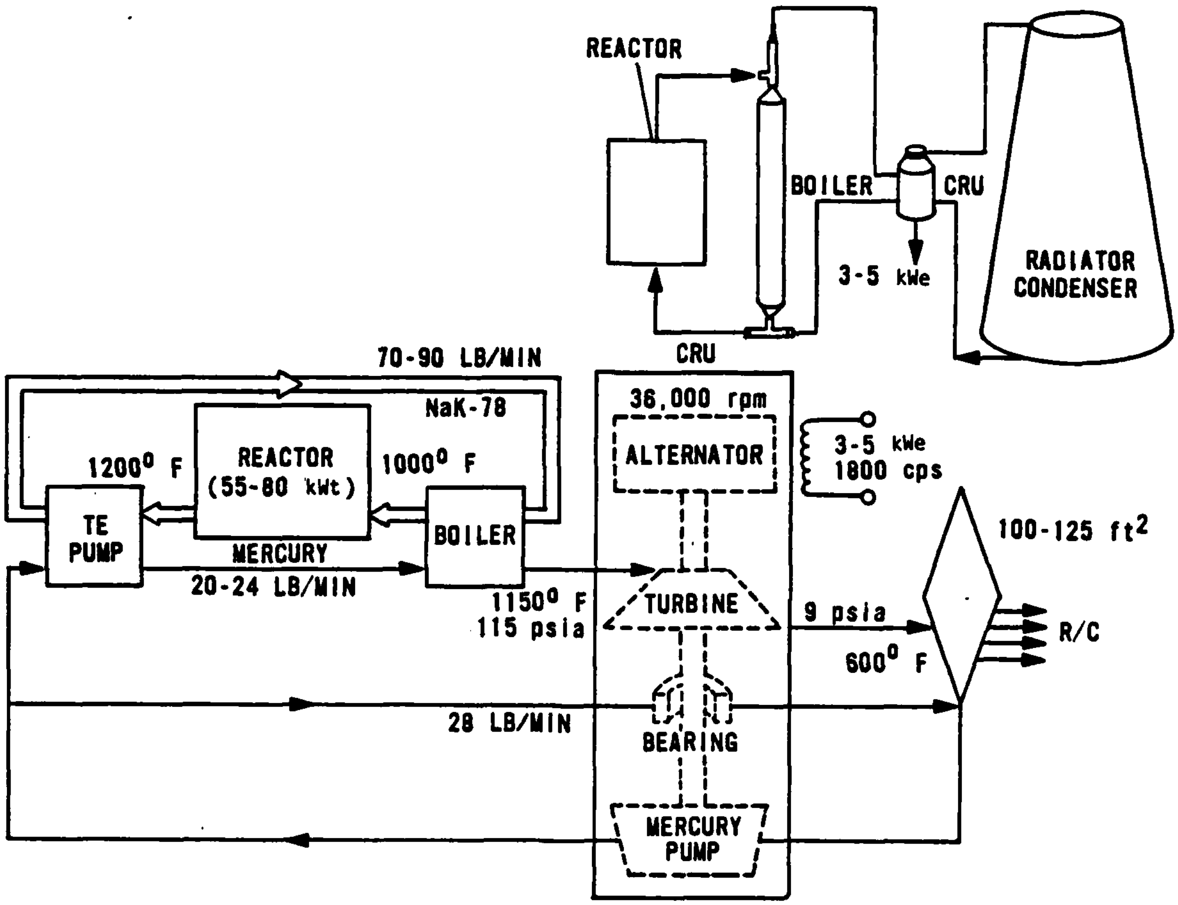

Figure 3. SNAP 2 Mercury-Rankine system schematic (after Ref. 3).

(a) The CRU-V was capable of providing 3.5 kWe or more during long-term endurance and design point operation with high intrinsic reliability. Three CRU-Vs were operated 2500 h or more; one operated 4759 h and was found to be in excellent condition upon disassembly. There was every indication that the developed hardware was capable of at least 10,000 h operation.

(b) The CRU-V was capable of successfully performing repeated injection-type start-ups with high reliability. One CRU-V successfully completed 37 start-ups with no reduction in performance. In tests of four CRU-Vs, the ability of the machinery to reliably complete start-up at preheat levels as low as 204°C was established.

(c) The CRU-V was capable of undergoing shock vibration levels characteristic of potential launch vehicles without adverse effect. Performance tests before and after shock vibration together with disassembly inspection indicated that the launch environment caused no performance loss or hardware damage.

(d) Substantial safe operating margins existed about the CRU-V nominal operating band. The CRU-V performance tests covering wide ranges for all key parameters gave no indication that limits were being approached or that unfavorable trends were developing.

(e) The CRU-V power outputs up to 5.6 kWe were demonstrated, and it was estimated that even higher outputs were possible with the present PM machine. If a Lundell type alternator was substituted for the PM type (within the rotor-stator envelope) power outputs of 9 kWe and higher would be possible with the same basic CRU design (Ref. 3).

Research was done on every facet of design for a complete power conversion system. Material testing was stressed to ensure a system capable of withstanding a high temperature, high radiation environment. Much of the research done was used in design of the SNAP 10A flight system which was actually flight-tested in 1965.

IV. SNAP EXPERIMENTAL REACTOR

The SNAP Experimental Reactor (SER) was the first one to be built by the specifications set down for space satellite applications. It was designed and tested by AI. Testing was conducted in an underground facility which housed the reactor system in a containment vessel with the heat exchange system located in the outer section (Fig. 4). Criticality was achieved in September 1959 and final shutdown of the system was in December 1961. A total of 5300 h of testing was completed at temperatures greater than 482°C.

SER CORE DESIGN

The SER core was cylindrical, having an outside diameter of 24.13 cm and a wall thickness of 0.24 cm (Fig. 5). The total core volume was 0.01 m^3. Both the top and bottom were penetrated by 3.18 cm coolant lines. The coolant was NaK which entered the core through lower inlet lines. The core vessel housed upper and lower grid plates which distributed the coolant in the core and held the fuel elements in place (Ref. 23).

FUEL/MODERATOR

The core consisted of 61 fuel elements arranged within a hexagonal array. The resulting interstices between the core vessel and fuel array were filled with Be sections, which acted as inner reflectors and physical barriers. Each fuel pellet was 2.54 x 2.49 cm dia. The fuel elements also acted as moderator to thermalize the neutrons, they were hydrided to a $N_h = 6.022 \times 10^{22}$ at/cm^3. The fuel was composed of a Zr-H alloy with 10 without U^{235} enriched to 93.12 percent. The alloy has a density of 5.58 kg/cm^3 and is 2.1 volume percent U and 97.9 volume percent ZrH (Fig. 6). The total fuel loading consisted of 3.0 kg of U^{235}.

The fuel cladding was fabricated of Hastelloy B, with an outside diameter of 2.54 cm and a wall thickness of 0.25 mm. The inside surface of the cladding was coated with a 0.05 to 0.08 mm layer of a B free ceramic coating which was Solarmic Coating No. 514-35A. Each fuel element was sealed at the ends by welding a 1.27 cm thick stainless steel endcap.

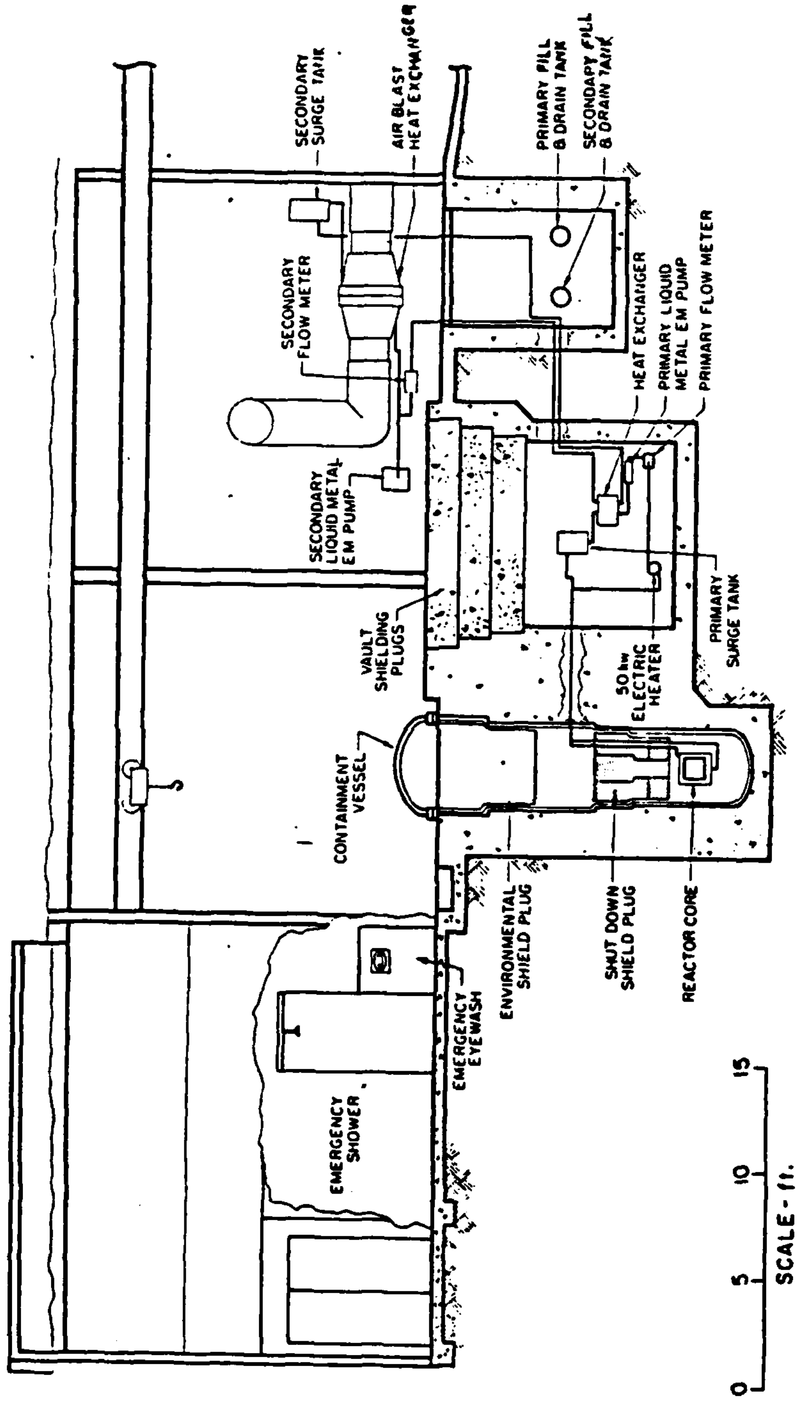

Figure 4. SER building elevation view (after Ref. 3).

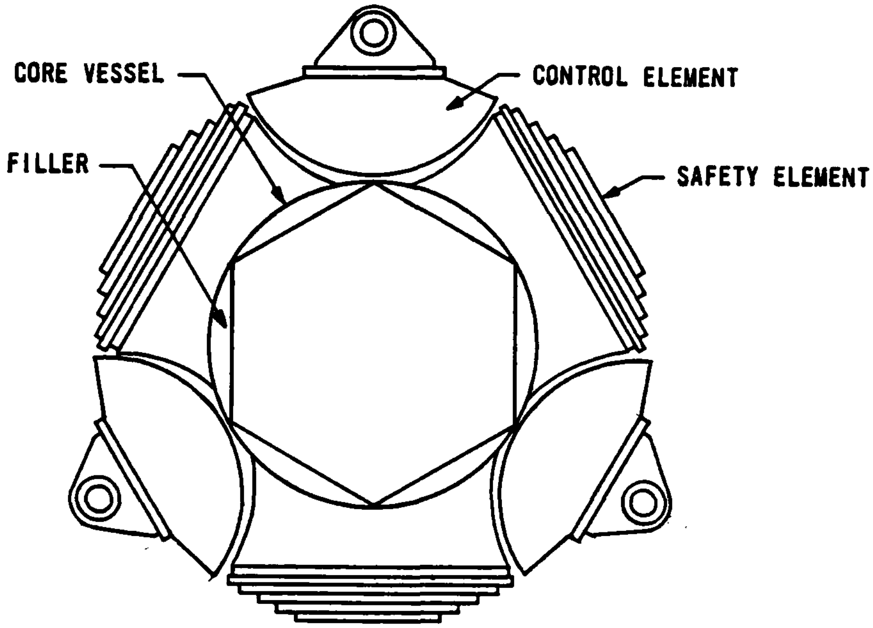

Figure 5. SER radial reflector cross section (after Ref. 3).

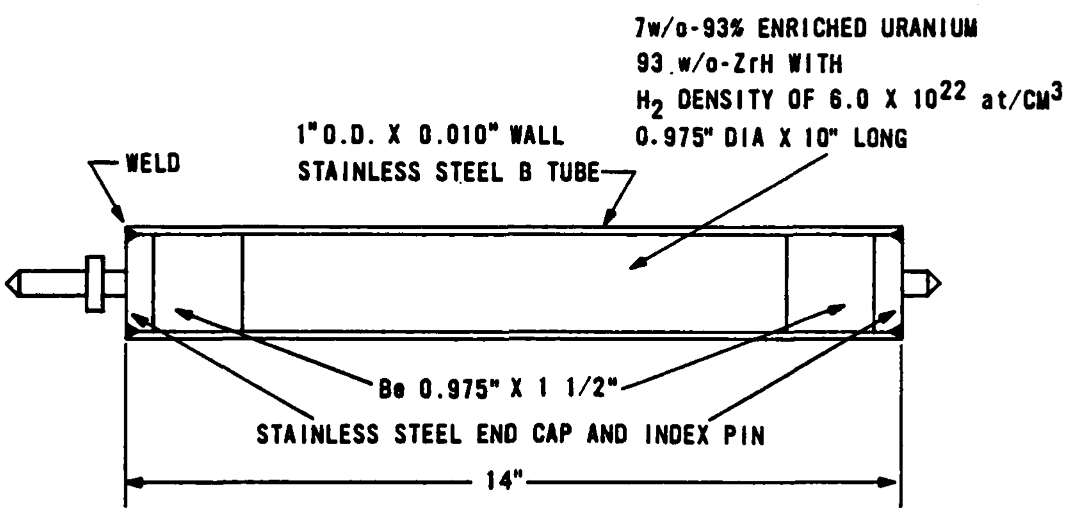

Figure 6. SER fuel-moderator element assembly (after Ref. 3).

REFLECTORS

Beryllium was used for the external reflectors. The system had three separate sections:

- 0.64 cm thick plates stacked along the three flat surfaces, also used for control,

- three partial circular drums which could be rotated away from the core, thereby, decreasing the amount of reflector surface. These were used for active control,

- and specially shaped pieces which filled the void left between the plates, the control drums, and the outer core vessel.

Beryllium was also placed within the core which filled the physical void between the circular vessel and hexagonal fuel array and acted as a reflector.

CONTROL

The control drums were rotated by a direct motor drive geared so that the maximum reactivity insertion was 0.015%/s (2.5¢/s). At the beginning of the operation, each control drum had a total worth of $3.82 when rotated from 0 to 180 degrees. Three independent safety elements were used both as reflectors and as a means of scramming the reactor system; they were each worth 5 percent in reactivity. Each safety element was pivoted about a hinge below the core. A scram was achieved by cutting power to the magnet which held them allowing them to fall from the core. A complete scram took 240 ms.

COOLANT SYSTEM

Eutectic NaK (78 weight percent K) was used as the coolant for the SER. It was pumped through a system consisting of an electomagnetic (EM) pump, a permanent magnet-type flowmeter, a plugging indicator for determining oxygen and/or precipitated hydrides in NaK and an intermediate heat exchanger (Fig. 7). The SER was tested independent of its energy conversion system.

The polyphase, linear induction EM pump was specially developed by AI for the SNAP reactor. It could circulate 1.45×10^{-3} m^3/s of 538°C eutectic NaK at a head of 0.84 kg/m^2.

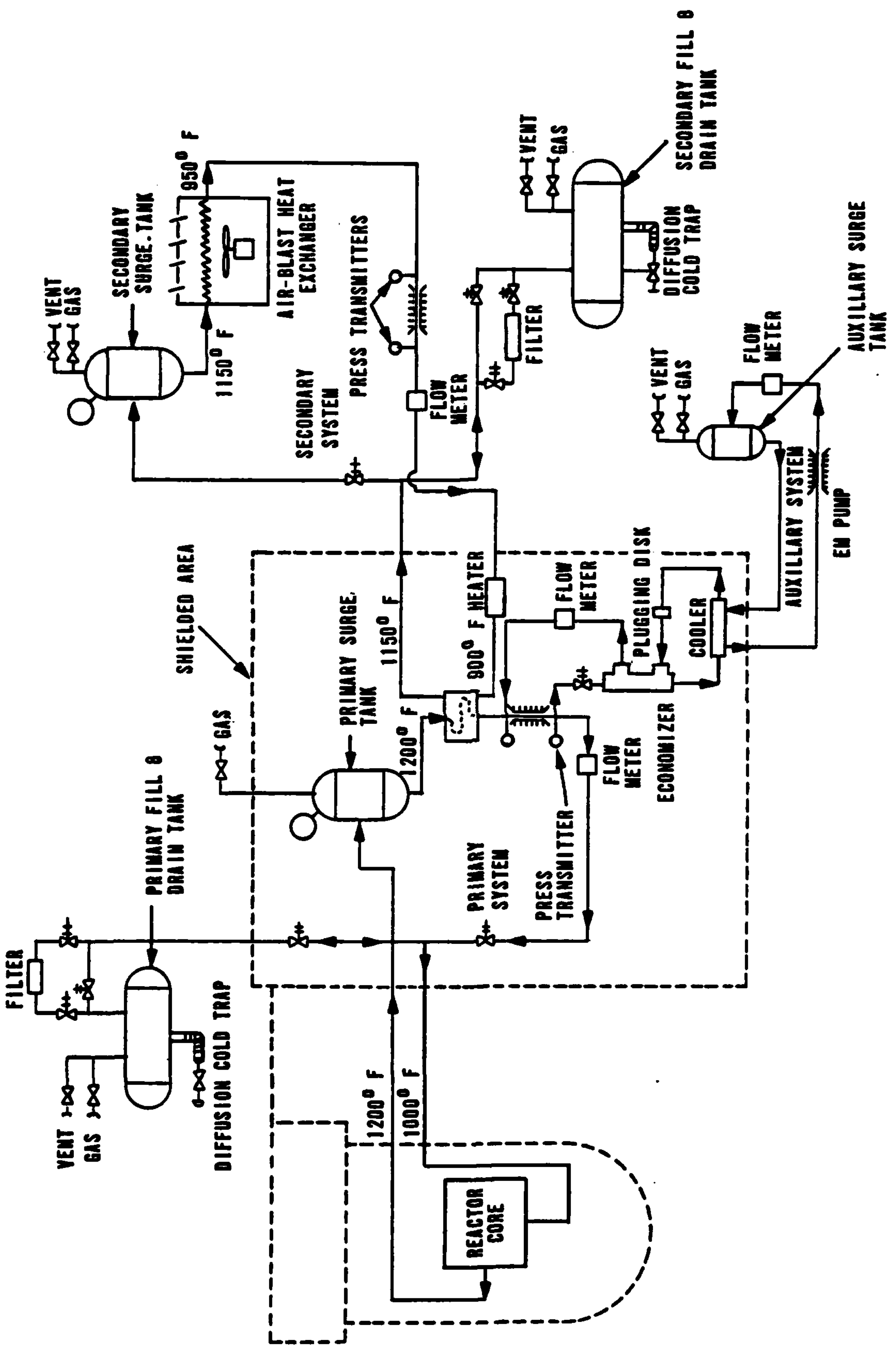

Figure 7. SNAP Experimental Reactor NaK coolant flow diagram (after Ref. 3).

OPERATING HISTORY

Full criticality of the SER was initiated on October 20, 1959 with final shutdown on November 19, 1960. It operated at up to 50 kW thermal, with a temperature output of 648.9°C for 1800 h and 482°C for 3500 h (Table 3). There was a total of 72 scrams throughout its operating lifetime (Table 4). Most were caused by minor difficulties which did not entail any major modifications to the system.

TABLE 3. SUMMARY OF SER OPERATION (after Ref. 3)

Initial fuel loading	September 17, 1959
Final shutdown	November 19, 1960
Elapsed time during testing	10,306 h, 440 days
Reactor operating time	6035 h, 58.5% of total time
Operation at 50 kW and 1200°F core outlet temperatures	1877 h, 31.1% of total operating time
Operation at 50 kW and less than 1200°F core outlet temperature	2290 h, 38.0% of total operating time
Operation less than 50 kW and less than 1200°F core outlet temperature	1868 h, 30.9% of total operating time
Reactor down time	4271 h, 41.5% of total time
Holidays and weekends	1288 h, 30.1% of total down time
Routine maintenance and experimental preparation	1245 h, 29.2% of total down time
Heater bundle failure	680 h, 15.9% of total down time
Other component failure	1058 h, 24.8% of total down time
Total energy generated	224.6 MW/h
Equivalent time at 50 kW	4493 h, 187 days

TABLE 4. SER SCRAM SUMMARY (after Ref. 3)

Number of Occurrences	Probable Cause
17	Abnormal signal in log power channels 3 and 4 and power level channels 6 through 8
15	Individual safety dropped out
13	Low "J" tub NaK level alarm
12	Circuit noise and accidental
6	False signal, source unknown
3	Disturbing of instrument cable in trench
3	Abnormal signal in startup channel (Channel 3) period instrumentation
1	Instrument trouble
1	Heater bundle failure
1	Electrical power failure
0	Initiated internal to core
72	Total through August 31, 1960

CONCLUSION

The two main objectives of the S2ER were to investigate: (a) The ability of the reactor to override reactivity losses associated with obtaining operating conditions and extended operation at these levels; and (b) to determine stability and safety of the reactor. Testing confirmed that the reactor was stable and capable of running for an extended period of time without an excess loss of reactivity.

The S2ER was considered a success. It gave continued confidence in the development of the SNAP program; it also led to in-depth research in component development.

V. SNAP 2 DEVELOPMENTAL REACTOR

The S2DR was the second reactor to be built and tested in the developing program of space reactors. The objective was to design and test the operability of a complete power plant system. It was the first model to use a flight control assembly. Studies were done on the reactor, individual components and the support system. The S2DR was tested and monitored so that it could be flight verified under the SNAPSHOT program. It was to be flight tested in September 1963 and January 1964, but the flights were cancelled due to a shift in the budget, which also resulted in the termination of the entire SNAP 2 reactor program with continued research being completed on the power conversion system.

The system was designed so that the nuclear reactor could be integrated with a Compact Power Unit (CPU). The CPU used a Mercury-Rankine cycle with a predicted power output of 3.5 kWe. Criticality was initiated in April 1961, with the final shutdown in December 1962.

CORE DESCRIPTION

The reactor vessel had a diameter of 22.86 cm, a length of 40.6 cm and a wall thickness of 0.16 cm. The reactor vessel housed the fuel pins, inner reflectors and grid plates (Fig. 8). The reactor and lower grid plates were fabricated from Hastelloy C and the upper grid plate of Carpenter LE-42 (Invar). The upper and lower grid plate held the fuel pins in place and distributed the coolant evenly through the core. The fuel was arranged in a triangular array, with a total of 37 fuel pins. The resulting reactor core was a right hexagonal cylinder about 20 cm across the flats, 23 cm across the corners and 24.5 cm long. Six radial pieces of Be were used to fill the voids between the fuel and the core vessel. These were used as inner reflectors as well as physical barriers.

The top and bottom vessel heads were conical with apex angles of 120 degrees. The core assembly was held in place by 12 Inconel-X springs compressed between the grid plate and the top head assembly. The six inner Be reflectors held the upper grid plate. The plate was not attached to the reactor vessel and, therefore, was free to expand axially with thermal changes. The bottom grid plate rested on a ledge machined into the bottom head assembly of the core vessel (Ref. 24).

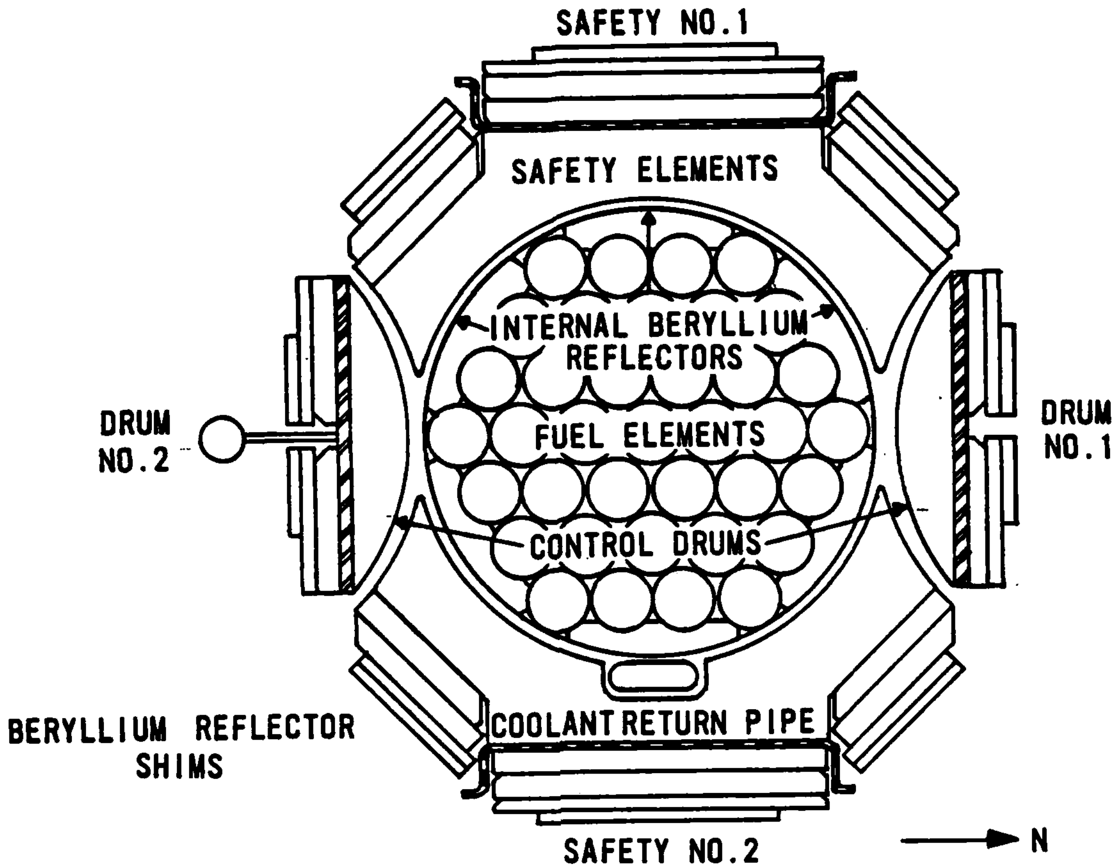

Figure 8. S2DR fuel rod assembly and core cross section (after Ref. 3).

The SNAP 2 working fluid was NaK (78% K). It was distributed through the bottom of the reactor vessel and through the lower grid plate. The flow then passed through the core into the plenum chamber between the top grid plate and the top vessel head. The flow then exited from the reactor head and was transferred to the primary and secondary head transfer loops.

The fuel elements were composed of 10 weight percent enriched U^{235}, 90 weight percent Zr-H and 0.1 weight percent C. The S2DR fuel rods were hydrided to an average of 6.44×10^{22} at/cm^3; therefore, acting as both the moderator as well as the fuel. The nominal, cold radial gap between the rod and the H barrier was 0.01 cm. The cladding was fabricated from Hastelloy N, chosen for its mechanical properties and its coefficient of expansion which is close to that of the fuel alloy. The mean coefficient of thermal expansion between 21°C to 648.9°C is 1.32×10^{-5} cm/cm°C for the Hastelloy N and 1.17×10^{-6} cm/cm°C for the fuel alloy (Ref. 25).

The cladding was coated with a ceramic barrier, Solaranic S 1435-SM2 which helped to minimize the loss of H. The loss of H was one of the major factors in the decrease of reactivity as a function of temperature and time. As the core temperature rose, the H dissociation pressure increased as did the permeation rate through the ceramic diffusion barrier. To accommodate the loss of reactivity, a thin layer of Sm was applied on the inside of the cladding which acted as a burnable poison.

The fuel elements were solid cylinders 25.4 cm long by 3.08 cm outside diameter (Fig. 9). The fuel cladding had an outside diameter of 3.18 cm and a wall thickness of 0.003 cm.

At each end of the fuel tube was a BeO piece which functioned as a reflector. The end pieces were 3.81 cm long by 3.08 cm in diameter and placed at each end of the fuel rod. The elements were sealed by welding the stainless steel fuel caps to the ends. The overall length of the fuel pins was 33.6 cm.

REFLECTORS

The core was reflected in four ways (a) Be pieces which fit into the end of the fuel elements, (b) inner reflectors which filled the interstices between the hexagonal fuel array and circular core vessel; (c) the rotating control drums, and (c) an external Be reflector 5.8 cm thick which surrounded the core vessel. The external reflector was split longitudinally into two halves, hinged at the bottom and retained at the top with a thin stainless steel band. During an actual flight, the separation of the band due to melting upon reentry or actuation of the band release devices would cause the reflector to fall away from the core and the reactor to shut down.

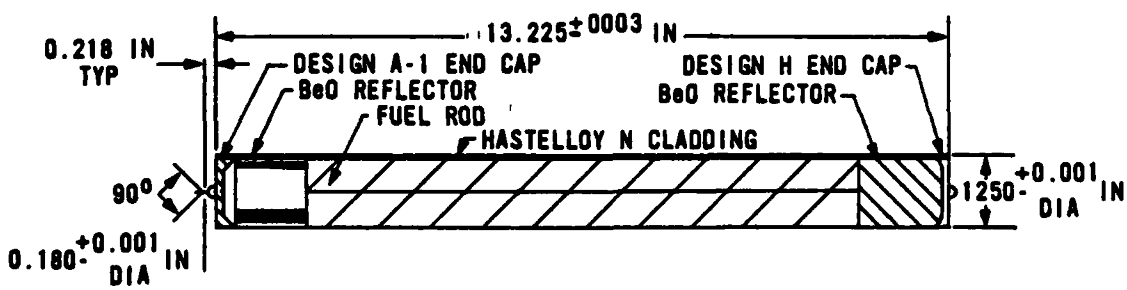

Figure 9. S2DR fuel element (after Ref. 25).

REACTOR CONTROL

The S2DR flight system was to be brought to critical by first locking two of the control drums into the outer reflector and then slowly rotating the other two into the external voids until criticality was reached. Power was to be maintained by adjusting the position of the two rotating control drums.

During ground testing the locked control drums were replaced by special safety elements which were designed to fall away from the core in the case of a scram. These were maintained at a full-up position unless scrammed. During testing the two Be control drums were mounted on the top and bottom flange assemblies which were maintained concentric with the reactor by four centering lugs. The control drums were rotated by constant-speed reversible motors at a rate of 0.56 deg/s, which corresponded to a maximum insertion of 2.1¢/s. Each of the control drums were connected directly to its drive motor through an antibacklash worm gear (Ref. 24).

SAFETY ELEMENTS

Safety drive mechanisms were located beneath the reactor which operated the Be safety elements. The two safety elements were mounted on the top and bottom flange assemblies which were maintained concentric with the reactor by four centering lugs. Limit switches were provided on each of the safety elements and control drums so that their action could be interlocked to ensure singular movement. Limit switches were used with the safety elements to determine full-up or full-down position. The safety elements were held up by electromagnets attached to the drive mechanism. The safety elements were dropped from the reactor during a scram by release of the electromagnet (Ref. 24). Figure 8 gives a clear picture of the safety elements and control drums for the S2DR.

S2DR REACTOR CORE TEST HISTORY

Significant operation milestones are presented in Table 5. Studies were done on (a) the rate of reactivity change caused by H loss and redistribution; (b) the transient response of the reactor to periodic variations of reactivity and flow; (c) the measurement of power coefficients of reactivity; and (d) the ability to hold up for long-term operations. The reactor was

TABLE 5. SIGNIFICANT MILESTONE DATES FOR S2DR OPERATION (after Ref. 3)

Milestone	Date
Facility (SETF) acceptance	12-05-60
S2DS installation completed	03-15-61
Initial criticality	04-03-61
Initial SNAP 10 design power and temperature	08-08-61
Initial SNAP 2 design power and temperature	06-26-62
Surpassed SER total energy release	10-30-62
Terminated power operation	12-11-62
Terminated nuclear testing	12-21-62

tested with changes in coolant inlet temperature and coolant outlet temperature. Also, the change in the reactivity loss rate over time was determined. There was a total of 39 scrams during the reactor's testing. See Table 6 for the complete scram outline. None of the scrams were initiated by system failure during the lifetime of the S2DR and only three due to instrument failures (Ref. 3).

CONCLUSIONS

There were no major problems in the testing of the S2DR. Testing allowed a closer look into the compatibility of the reactor's materials, ability to operate in a radiation environment and to withstand thermal cycling. The experimental program allowed evaluation of operating characteristics such as long-term reactivity loss rate, Xe poisoning effects and H redistribution effects. These characteristics were used to evaluate the performance of other SNAP reactors (Ref. 24).

TABLE 6. S2DR REACTOR SCRAMS (after Ref. 3)

Reason	Number of Scrams
Spurious noise (Channel 4, startup level)	7
Spurious noise (Channel 6, intermediate level)	2
Spurious noise (Channel 7, intermediate level)	11
Power fluctuation	14
Contractor (severed feed line)	1
Primary NaK flow loss during plugging run	3
Primary NaK flow loss during flow oscillation	1
Instrument malfunction	
NaK level recorder	1
Core temperature recorder	1
Fuel temperature recorder	1
Operator (checking equipment during operation)	5

VI. SNAP 8 SYSTEM OVERVIEW

The SNAP 8 nuclear reactor was designed to produce approximately 35 kWe output for use in space. The major performance objectives being 600 kW of thermal power, 704.4°C NaK outlet temperature, 10,000 h endurance, orbital start up and automatic control, high reliability and low weight (Ref. 26).

The following statement was given by President Kennedy in a "Report to the Congress from the President of the United States" and included in the report "United States Aeronautics and Space Activities 1962," January 18, 1963 (Ref. 27).

> "The SNAP-8 Electric Power Generation System will provide power for advanced space missions, such as lunar stations or orbiting space platforms, and for interplanetary communications. In addition, SNAP 8 may provide an early electrical propulsion capability. It is also designed to provide some advanced technology which will be required for higher powered nuclear electric systems in the megawatt range."

In the 1960s the value of a space reactor was recognized at many levels in the political echelon.

The SNAP 8 was a joint project between AEC and NASA. The AEC was responsible for the nuclear system and ground testing of the complete electrical generating system. The NASA was responsible for the power conversion system, the spacecraft, for nonnuclear testing of the electrical generating system, and for flight testing (Ref. 27). A Mercury-Rankine cycle power conversion system was developed by Aerojet General Corporation (Ref. 27).

Testing was completed on two prototypes of the SNAP 8 reactor design: the S8ER and S8DR. The main conclusions drawn from these two tests was the need to improve fuel rod design and the thermohydraulics of the system.

A Mercury-Rankine cycle power conversion system was to be used with the SNAP 8 reactor (Fig. 10). NASA was helping to develop four dynamic power conversion systems for space applications: an organic Rankine, the SNAP 8 Mercury-Rankine, a potassium-Rankine and the Brayton cycle. As of April 1970, the Mercury-Rankine development was further along than the other systems.

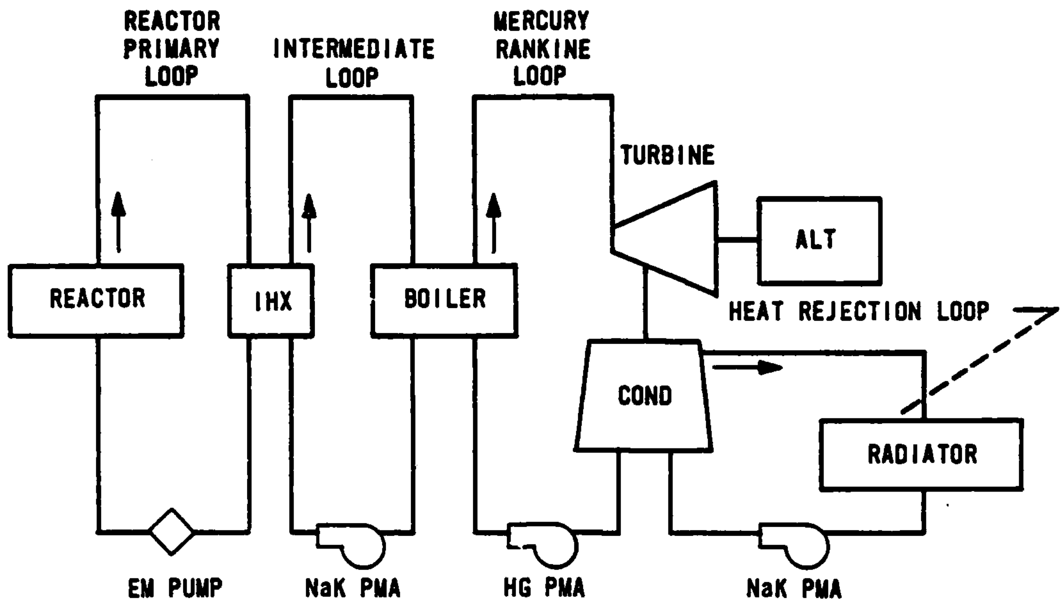

Figure 10. SNAP 8 system (after Ref. 28).

A Mercury-Rankine system was tested for 7320 h without replacement of any components. Every major component was tested at design conditions for at least 10,000 h. The power conversion system was also started and stopped 135 times to study its flexibility and durability. Posttest examination showed that, with a single exception, the components were in good shape. The single exception was the mercury pump in which some cavitation damage was found on the rear face of the impeller of the centrifugal pump (Ref. 28).

It was concluded in Ref. 18 that the SNAP 8, using a Mercury-Rankine conversion system, appears to be capable of producing 50 kWe at a reactor outlet temperature of 660°C and if the reactor-life predictions were realized, for about 40,000 h. The estimated weight for a 30 kWe SNAP 8 system, including shielding was 2873 kg (Ref. 29).

VII. SNAP 8 EXPERIMENTAL REACTOR

The S8ER was used as a proof-of-concept test reactor. The design performance objectives of the SNAP 8 were 600 kWt power output, 704°C NaK outlet temperature and 12,000 h power operation with high reliability. Testing was performed in a dry He atmosphere at AI Nuclear Development Field Laboratory. The S8ER was tested from May 1963 to April 1965. A complete outline of the S8ER is presented in Table 7.

Operation of the S8ER demonstrated:

(a) Sustained power operation capability. The S8ER released greater than 5.1×10^6 kWh of energy during 500 days of nuclear operation, including 100 days of 600 kWt and 704°C outlet temperature and 365 days at more than 400 kWt and 704°C outlet temperature.

(b) Static and dynamic stability.

(c) Acceptable integrity of the interim H barrier coating on the cladding tubes.

(d) Capability of tolerating rapid changes in the power level. During the power coefficient measurements, the core was subjected to about 155 rapid changes in power (100 kWt in 1 min.).

(e) Verification of SNAP 8 reference design (Ref. 30).

REACTOR DESCRIPTION

The reactor contained 211 fuel-moderator elements. Each element consisted of an individual fuel rod, a H diffusion barrier containing burnable poison, exterior cladding, endcaps and grid plate indexing pins (Fig. 11).

The fuel was 93.15 percent enriched U^{235} in a solid Zr-U alloy (10% U) hydrided to a density of 6.0×10^{22} at/cm^2. The outside diameter of the fuel rod was 1.35 cm with an active length of 35.56 cm. The diametrical gas gap was 3.2 mils (cold). A ceramic coating (Al-87630), 7.6×10^{-4} cm thick, was applied on the inside of the fuel cladding to prevent the loss of H. A burnable poison, Sm_2O_3, was added to the ceramic coating, approximately 1.35 mg Sm_2O_3 per linear centimeter of fuel element. The burnable poison compensated for the excess reactivity at the beginning-of-life and helped to maintain a relatively constant power level.

TABLE 7. S8ER DESIGN ·ATA SUMMARY (after Ref. 34)

Design Parameters	
Design power level	600 kWt
Life	10,000 h
Primary coolant	NaK 78 eutectic
Secondary coolant	Nak 78 eutectic
Number of fuel elements	211
Fuel loading	6.56 kg of U enriched 93.15%
Reflector	7.62 cm nominal thickness Be
Control	6 rotating control and safety drums
Fuel Elements	
Composition	Hydrided Zr-U alloy
Hydrogen concentration	6×10^{22} at/cc
Alloy	90 wt % Zr - 10 wt % U
Cladding (Hastelloy N)	0.0254 cm walls and 0.635 cm end caps
Fuel rod diameter	1.35/cm
Fuel rod length	35.56 cm
H_2 diffusion	0.00762 cm thick ceramic coating on inside of cladding surface
Burnable poison	48 mg of SM_2O_3 per element
Maximum cladding temperature at design power level	782°C
Maximum core temperature at design power level	839°C
Reactor Core	
Core vessel size	23.72 cm OD by 53.34 cm nominal height
Core vessel material	316 SS
Core vessel wall thickness	0.16 cm
Upper grid plate material	316 SS
Upper grid plate diameter	23.34 cm
Upper grid plate thickness	0.873 cm
Upper grid plate coolant passages	420 0.397 cm dia holes
Lower grid plate material	Hastelloy C
Lower grid plate diameter	23.34 cm
Lower grid plate thickness	0.794 cm
Lower grid plate coolant passages	420 0.318 cm dia holes
Internal reflector	18 BeO filler pieces
Internal reflector cladding	Hastelloy N
Control and Safety Elements	
Number of elements	6
Material	Be
Length	36.83 cm
Drum radius of curvature	11.91 cm
Nominal thickness	7.62 cm
Weight of each control element (including support and shim)	12.02 kg
Radial bushing clearance (self aligning)	0.004 to 0.006 dia
Friction torque	1.13 N/m

TABLE 7. (Concluded)

Control Element Drives	
Drive means	1 reversible a-c motor per control element (only one element can be inserted at one time)
Element rotation rate	0.055 rpm (2¢/s)
Element rotation range	105 deg
Time to rotate full range	319 s
Coast rotation	0.033 deg (0.2¢)
Rotation stops	Limit switches and mechanical stop
Overload protection	Slip clutch
Drive system backlash	None - taken out by scram spring
Scram System	
Scram Power	Torsional spring
Scram torque	3.387 N/m total 2.258 N/m for acceleration
Scram activation	Deenergizing of electromagnetic clutch
Primary Coolant	
Flow rate	0.0083 m^3/s
Reactor inlet temperature	593°C
Reactor inlet pressure	0.0113 kg/m^2
Reactor outlet temperature	704°C
Reactor outlet pressure	0.0108 kg/m^2
NaK inventory	142.8 kg
Secondary Coolant	
Flow rate	0.0083 m^3/s
Heat exchanger inlet temperature	566°C
EM pump inlet pressure	0.0089 kg/m^2
Heat exchanger outlet temperature	677°C
EM pump outlet pressure	0.0159 kg/m^2
NaK inventory	282.1 kg
Nuclear Characteristics	
Lattice spacing	1.45 cm
Mean prompt neutron lifetime	6.7 μs
Effective delayed neutron fraction	0.0077
Median fission energy	0.21 eV
Thermal flux	2×10^{12} $n/cm^2/s$

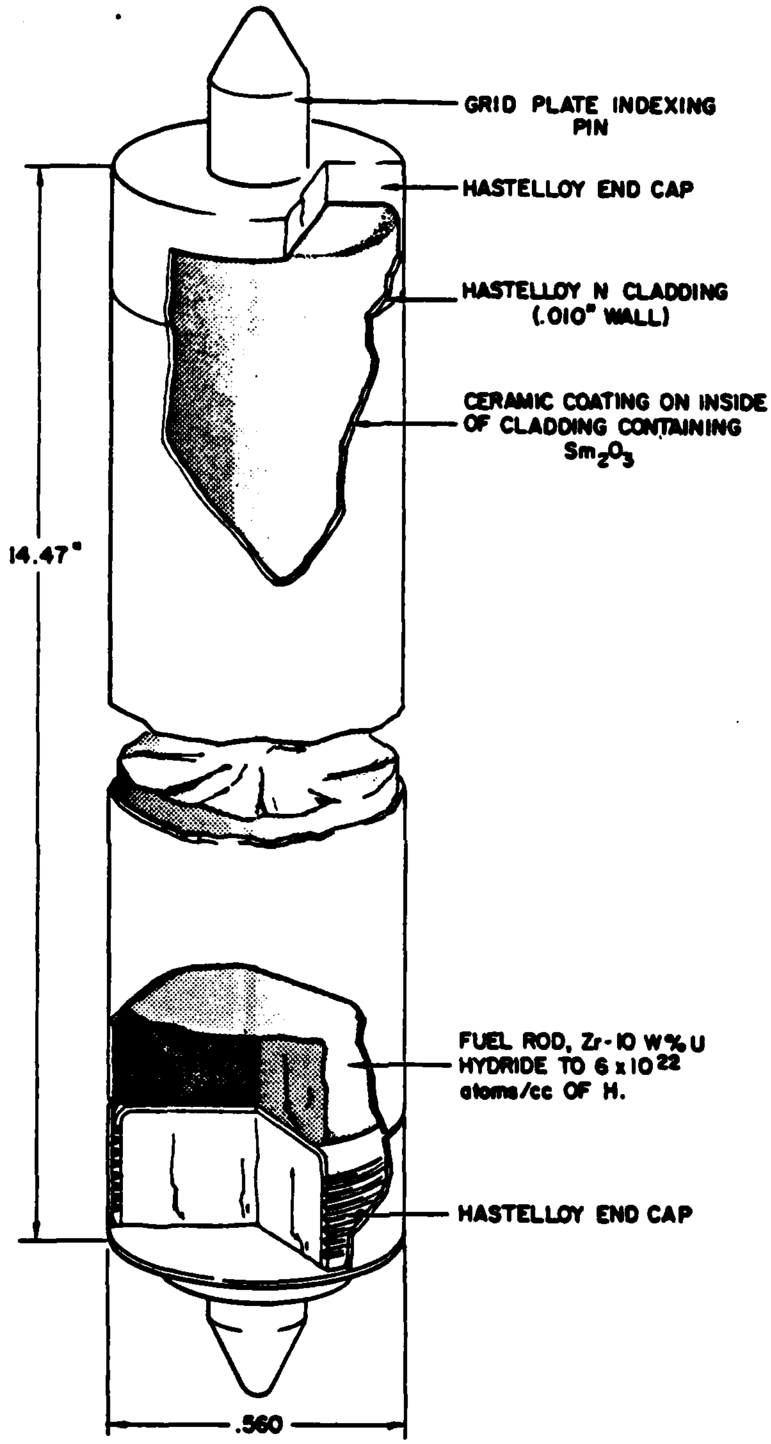

Figure 11. S8ER fuel element (after Ref. 7).

The cladding was 2.54×10^{-2} cm thick, it was fabricated from Hastelloy N. Endcaps made from Hastelloy N were seal welded to the tubings. The fuel elements were arranged in a hexagonal array. They were held in place by end pens which fit into the upper and lower grid plates. Figure 12 is a schematic of the S8ER fuel pin (Ref. 7).

The circular core vessel was fabricated from Hastelloy N. It was 53.34 cm long with an outside diameter of 23.72 cm. The core vessel was 0.27 cm thick. The upper grid plate was fabricated from 316 stainless steel and the lower of Hastelloy C. There were 18 internal BeO reflectors with Type 316 stainless steel casings. These were used to fill the interstices between the fuel and core vessel.

REFLECTOR SYSTEM

A solid layer of Be, 7.62 cm thick, surrounded the active length of the core vessel. It was composed of two halves pinned together. The reactor was subcritical with this single layer of Be. Criticality was brought about by the rotation of the six control drums located outside of the Be ring. The control drums were half segments of right circular cylinders fabricated from Be. Each reflector drum was driven by its own mechanism. The control drums were used to vary the amount of neutron leakage from the core and, therefore, control the power level.

Three of the control drums were used for start-up and were driven in by springs. The other three reflector drums were used for fine control and were driven stepwise by long-term directional control drum actuators. The control drums were also used as safety elements to scram the reactor. A release mechanism would allow the control drums to fall away from the core vessel, thereby causing the reactor to shutdown.

During testing, removable shims were used on the back of the control drums to permit adjustments of its worth prior to reactor start-up. Position readout and limit switch information were also included during testing (Ref. 7).

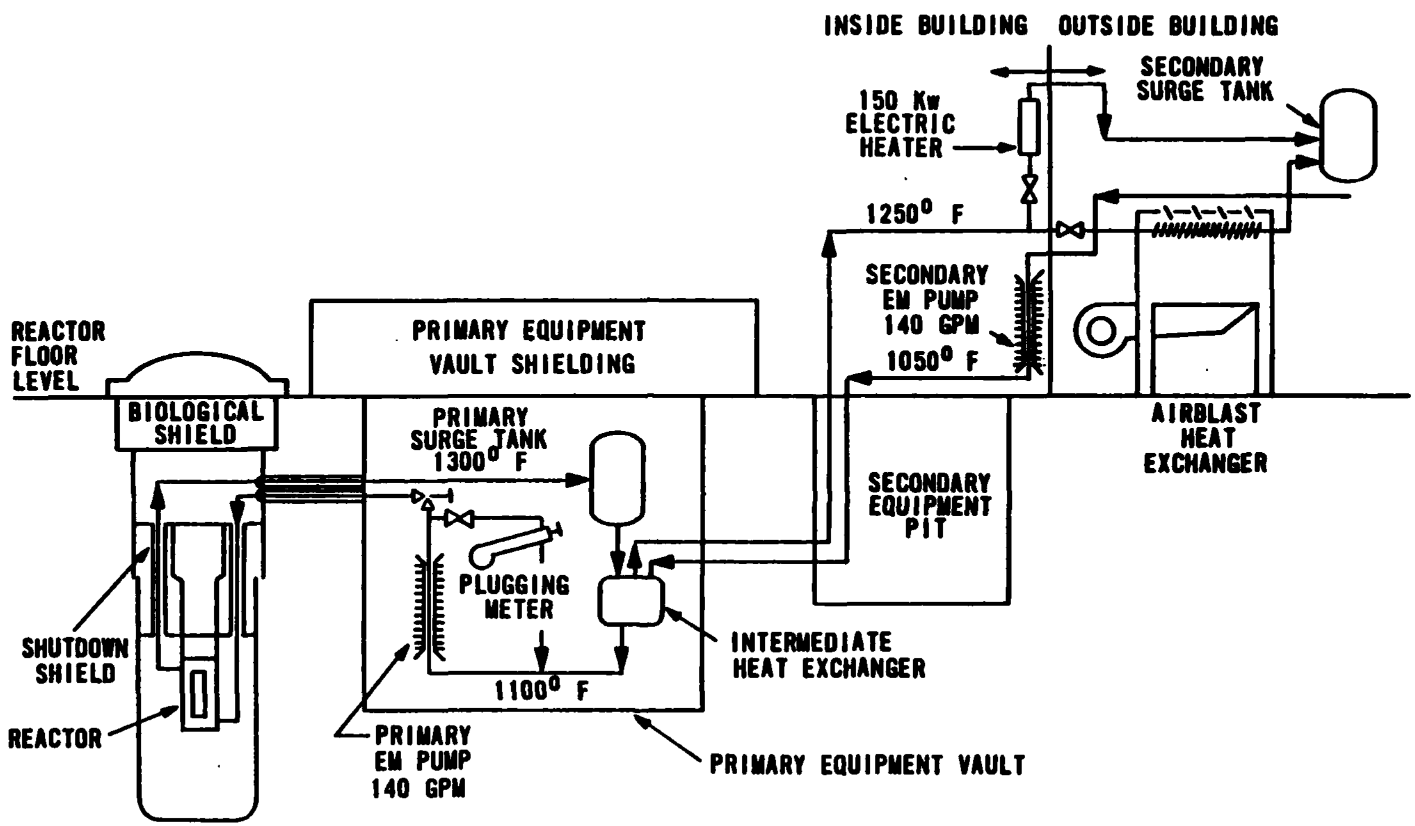

Figure 12. S8ER test facility (after Ref. 32).

HEAT TRANSFER SYSTEM

Heat from the core was removed by the primary coolant system. The working fluid was eutectic NaK (78% K). Heat from the primary coolant system was rejected to the NaK secondary coolant system through an intermediate heat exchanger. The secondary system rejected heat to the atmosphere by means of an air-to-NaK heat exchanger. The coolant was circulated by an electromagnetic pump.

REACTOR FACILITIES

The S8ER was tested below ground in a shielded containment vessel (Fig. 12). The reactor core assembly was suspended by the shutdown shield, which was a high density borated concrete, lead insulated air-cooled barrier. Above this were the control drive mechanisms and primary coolant piping. Helium was used inside the pressure vessel to help slow corrosion of the Be reflectors. Water cooling coils encircled the 1.91 cm thick carbon-steel containment vessel (Ref. 32).

CONCLUSION

In posttest examinations of the S8ER, fuel rod-bowing was not observed, but in one case ovality was found, and this was a massively dehydrided rod. From the metallographic examination it was concluded that a large portion of the core had undergone phase change (Ref. 33). The maximum density changes observed in the S8ER fuel elements appeared to correlate best with the calculated two-phase region β-S. This was also the region of maximum calculated temperature which was believed to contribute to a low H region (Ref. 34).

VIII. SNAP 8 DEVELOPMENTAL REACTOR

The S8DR was a prototype flight system tested to provide long-term operating experience at rated conditions and to verify the reliability of the reactor support system.

The design objectives of the S8DR were to maintain a power output of 600 kWt, a coolant outlet temperature of 704°C and an operating lifetime of 12,000 h. Testing of the reactor core began in January 1969 and ended prematurely in December 1969 after approximately 7000 h of operation. Testing was ended due to indications of ruptured fuel cladding (Ref. 35). An outline of the S8DR is presented in Table 8.

REACTOR DESCRIPTION

The S8DR was a modified version of the S8ER core design, the major changes were:

- longer fuel rods and reactor vessel,
- an improved hydrogen retention barrier,
- larger radial and axial gas gaps between the fuel and cladding,
- an improved coolant flow profile within the core (Ref. 36).

The S8DR was a Zr-U alloy with 10.5 weight percent U. The U was 93.15 percent enriched U^{235}. The fuel was hydrided to an N_h = 6.0 x 10^{22} at/cm^3. The fuel rod had a diameter of 1.34 cm and an active length of 41.91 cm. The axial gas gap was 240 mils, with a diametral gas gap of 7.0 mils. The fuel cladding was fabricated from Hastelloy-N. It was 43.51 cm long, 0.025 cm thick and had an inside diameter of 1.37 cm. A ceramic barrier was applied on the inside of the fuel cladding to retard H diffusion through the cladding. The S8DR used SCB-1 as its ceramic barrier. The SCB-1 has greater resistance to thermal shock than Al-87630 which was used on the S8ER. A burnable poison was also applied to the inside of the cladding to compensate for long-term reactivity losses. The poison, Sm_2O_3, was blended in the ceramic barrier material for this purpose.

The reactor core vessel was fabricated from 316 SS. It was 66.65 cm long with an internal diameter of 23.40 cm and was 0.2667 cm thick (Fig. 13). The core had a total of 211 fuel elements arranged in a triangular array on a

TABLE 8. S8DR CHARACTERISTICS

General	
Design Power Level	600 kWt
Reactor outlet temperature	704°C
Reactor inlet temperature	593°C
Average power density	37 kW/L of core
Maximum Power Level	1 MWt
Reactor outlet temperature	593°C
Reactor inlet temperature	443°C
Design Life	12,000 h
Primary Coolant	NaK
Secondary Coolant	NaK
Number of Fuel Elements	211
Fuel Loading	8.2 kg U enriched to 93.15% U^{235}
Reflector	13.018 cm, normal thickness
Control	6 rotating Be reflector drums
Reactor Core	
Core Vessel Size*	23.480 cm ID by 81.788 cm height to outlet line
Material	316 stainless steel
Wall thickness	0.231 cm
Grid Plates	
Coolant passages	420(0.396 cm dia)
Spacing of Fuel element positioning holes	1.455 cm (triangular lattice)
Spacing of coolant holes	0.841 cm (hexagonal lattice)
Upper grid plate	
Material	316 stainless steel
Diameter	23.411 cm
Thickness	2.159 cm
Lower grid plate	
Material	Hastelloy C
Diameter	23.411 cm
Thickness	1.651 cm
Internal Reflectors	
Material	30 stainless-steel clad BeO and 12 solid stainless-steel pieces
Cladding thickness	0.076 cm
Cladding material	316 stainless steel
Fuel Elements	
Fuel Rods	
Composition	Hydrided ZrU alloy
Fuel	10.5 wt % U
Enrichment	93.15 wt % U^{235}
Hydrogen concentration	6.05×10^{22} at/cc
Diameter	1.344 cm
Length	42.736 cm
Axial hydrogen gap	0.610 cm
Radial hydrogen gap	0.089 mm
H_2 diffusion barrier	0.051 mm ceramic coating on inside of cladding surface

*All dimensions are at room temperature conditions unless otherwise specified.

TABLE 8. (Concluded)

Burnable Poison	58 mg Sm_2O_3/element (in ceramic)
Cladding (Hastelloy N)	1.372 cm ID, 11.3 mils thick
Fuel Elements	
Diameter	1.430 cm
Length	44.006 cm (excluding positioning pins)
Peak fuel temperature at design power level	807°C
Peak Cladding temperature at design power level	742°C
Average fuel burnup (12,000 h at 600 kW)	0.22 metal atom %
Control Drums	
Number of Drums	6
Material	Be
Length	39.052 cm (total reflector length 46.99 cm)
Drum Radius of Curvature	11.43 cm
Nominal Thickness	13.018
Drive Means	Electromagnetic stepping motor
Rotation Range	0 to 109°
Full-In Stop	1.0 ± 1.0
Full-Out Stop	135 ± 2.0
Drive-System Backlash	±0.05°
Scram Power	Torsional spring
Nuclear Characteristics	
Mean Prompt Neutron Lifetime	8.4 μs
Effective Delayed Neutron Fraction	0.0080
Median Fission Energy	0.15 eV
Thermal Flux @600 kW (<1 eV)	3×10^{12} n/cm^2 s
Radial Peak to Average Power	1.29
Axial Peak to Average Power	1.36
Clean, Wet, Excess Reactivity	$14.40
NaK Reactivity Worth	$0.25
Total Isothermal Temperature Coeff. of Reactivity	-0.18¢/°F at 21°C -0.20¢/°F at 649°C
Power Coefficient of Reactivity	-0.035¢/kW
Rise to 600 kW Power and 1200°F Core Average Temperature	-2.15
Reactivity Inventory (12,000 h)	
Hot, end of life excess (600 kW)	$5.45
Samarium burnout	$2.90
Fission product poisoning	
Xe	-$1.05
Sm	-$1.02
Other	-$1.17
Axial hydrogen redistribution	-$0.65
Hydrogen loss	-$5.15
U^{235} burnup	-$0.66
Control Drum Worth	
Total - 6 drums	$21.06
Single drum	$ 3.90
Maximum differential worth	5.75¢/deg
Thermal and Hydraulic Characteristics	
Average Heat Flux (at 600 kW)	148,144 W/m^2
Fuel to Coolant Heat Transfer Area	4.05 m
Collant Flow Area in Core	
Cold	57.04 cm^2
Hot	60.664 cm^2
Hydraulic Diameter (individual coolant channel)	2.057 mm
Mass Flow Through Core (600 kW and 200°F ΔT)	6.144 kg/s
Average velocity through core, hot	1.402 m/s
Mass Flow Through Core (1000 kW)	7.554 kg/s
Average velocity through core, hot	1.707 m/s

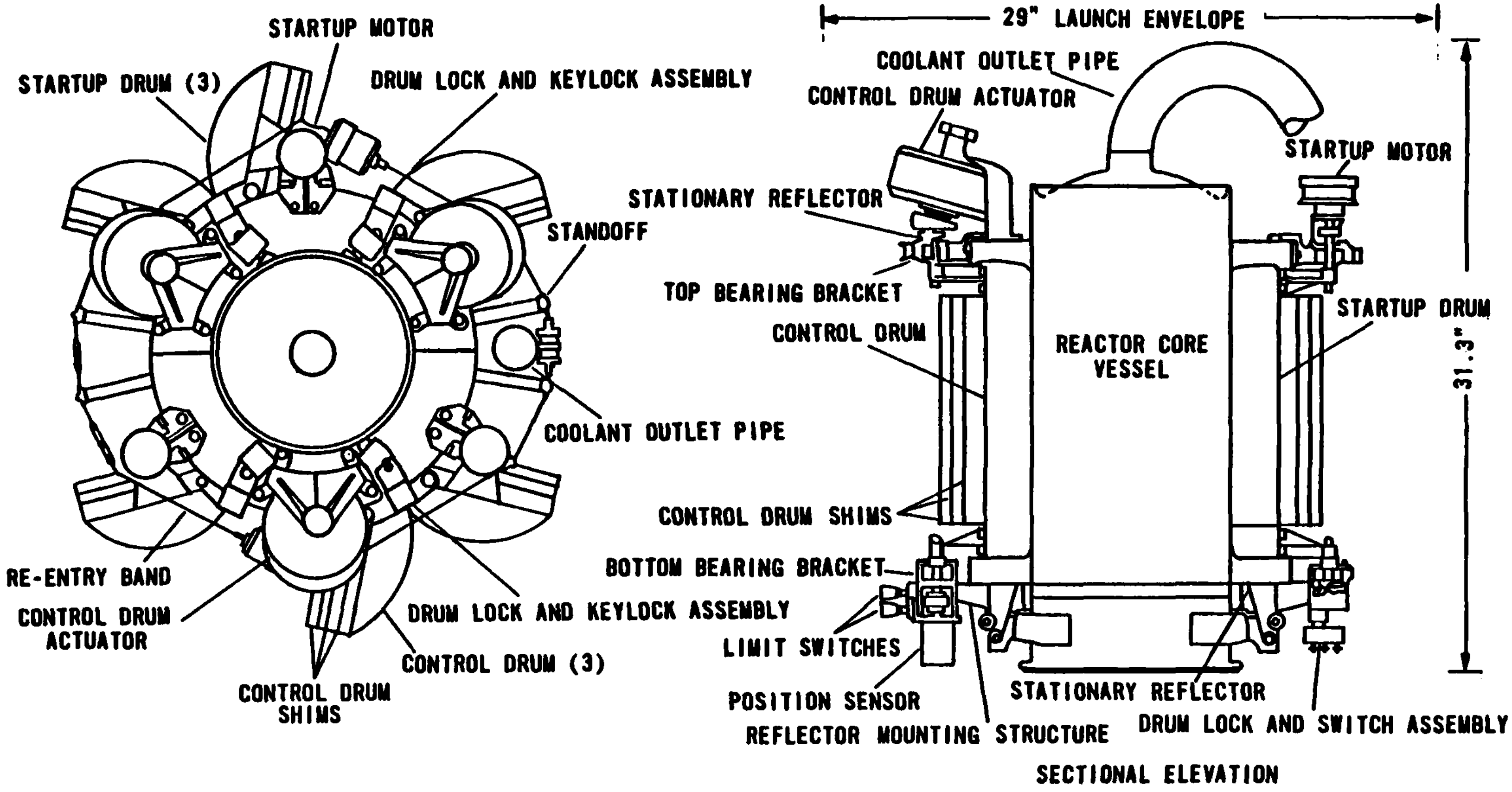

Figure 13. SNAP 8 reactor and reflector assembly (after Ref. 26).

1.45 cm centerline spacing. The fuel was held in place by end pins which fit into the upper and lower grid plates. Internal reflectors were placed in the voids between the circular core vessel and the triangular fuel array. Thirty BeO inner reflectors clad in 316 SS were used along with 12 smaller filler rods of 316 SS. A 0.1 Ci Po-Be source was located at the top head of the vessel (Fig. 14).

A flow distribution and a flow baffle plate, both fabricated from Hastelloy C, were located below the lower grid plate. The flow distributor was a basket shaped piece with a wedge facing the nozzle. It had 64 holes around the side to distribute the flow evenly to the baffle plate. The baffle plate was a disk with 73 holes sized and shaped to provide the desired flow distribution in the core.

The coolant used was eutectic NaK (78% K). The coolant entered the lower plenum through the flow distributor, through the baffle plate and into the 420 tricusp coolant channels between the fuel elements. The coolant then continued upward through the coolant channels and exited through the upper grid plate into the upper plenum. The upper grid plate was fabricated from 316 SS. The coolant then mixed in the upper plenum and exited through the reactor outlet pipe. In-core thermocouples were used to monitor 27 of the upper grid plate flow channels. The thermocouples were held in place by a bridge which positioned the junctions at the centers of the coolant passages just over the top surface of the grid plate (Ref. 37).

REFLECTOR AND CONTROL SYSTEM

The SNAP 8 system was designed to operate from 10 to 100 percent of its rated power. The power level was adjusted by an automatic controller which sensed the reactor coolant outlet temperatures and adjusted the position of the control drums to maintain the proper outlet temperature (Ref. 38).

The complete reflector system was designed in two halves. Each half was supported by a hinged-pivot fixture on the bottom of the core vessel (Fig. 15). The reflector halves were designed to bear against support brackets at the top of the core vessel. They were held in place by a thin steel tension band wrapped around the outside. It was also designed so that when used on an actual flight system, the reflectors could be removed from the reactor.

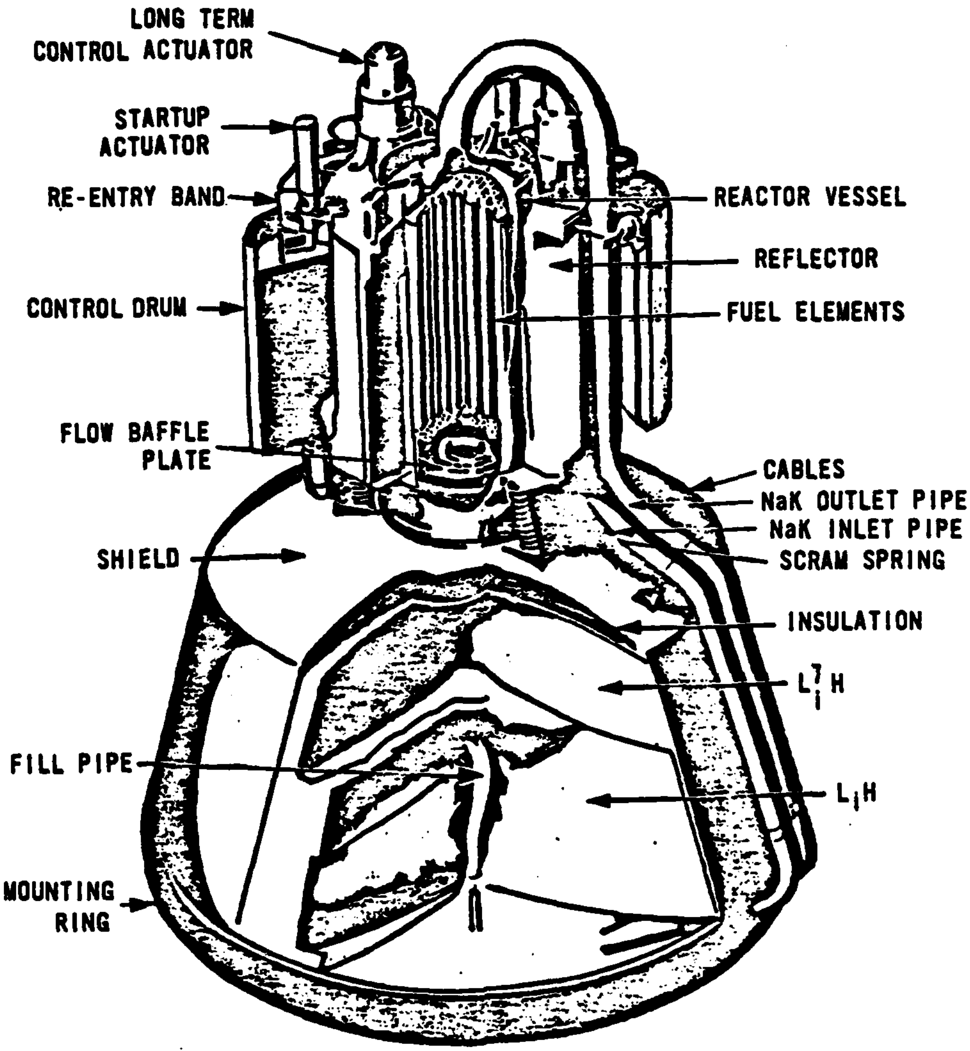

Figure 14. Frontispiece: SNAP 8 nuclear system.

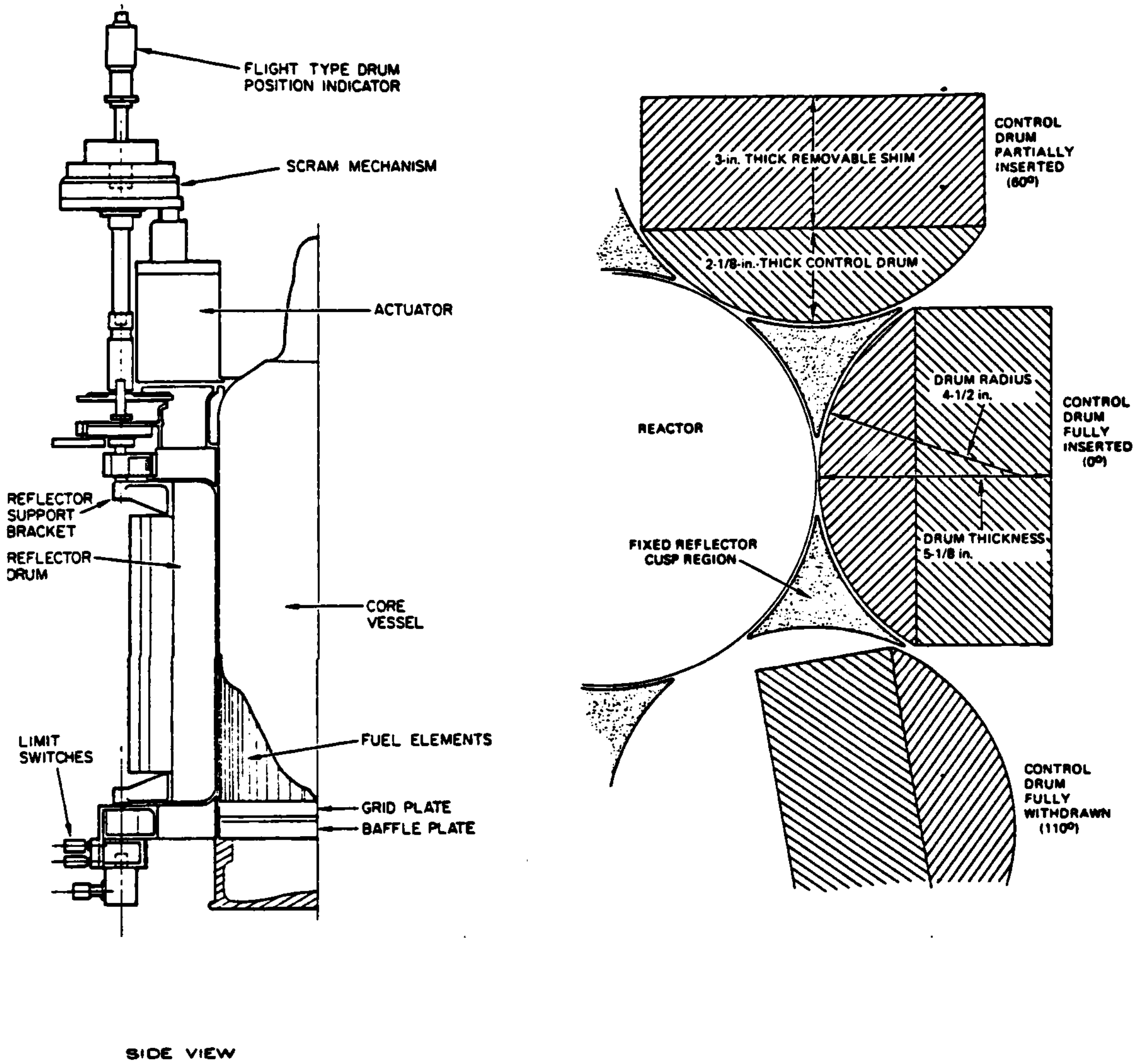

Figure 15. Reflector and control drums for SNAP 8 developmental reactor (after Ref. 39).

Immediate shutdown of the reactor could be achieved by breaking the retaining band, thereby ejecting the reflector assembly. This form of shutdown would occur as a result of:

- command destruct,
- a temperature drop in the coolant outlet line,
- or reentry heating.

If the reflector was ejected from the reactor, the reactor could not be made critical unless the core was immersed in water or other moderating material (Ref. 38). A shaped destruct charge (which could disperse the core components) was another safety feature being considered. This would guarantee that the reactor would not become critical during launch and preorbital operations. The charge would only be allowed to detonate with a signal from ground command. After the spacecraft was successfully in orbit, the destruct system was to be ejected. The ejection was to be accomplished by firing pyrotechnic pressure cartridges which would pull a pin on the destruct charge assembly. The assembly was to be jettisoned away from the core by a preloaded spring (Ref. 38). These safety precautions were not used for the S8DR ground test, rather emergency shutdown was achieved by snapping the control drums to a full-out position using scram springs.

The reflector assembly consisted of an annulus of Be which surrounded the length of the core vessel and six movable reflector drums. The annulus of Be was 8.89 cm thick and approximately 45 cm long. External Be cusps were attached to the core vessel and spaced so that they provided a half circle in which the control drums could rotate. Control of the reactor was achieved by rotation of six right circular cylinders of Be. The control drums had a radius of 11.4 cm and a nominal thickness of 7.94 cm. The cylinders were rotated into half circular voids, thereby, controlling the neutron population within the core.

Three of the six control drums were used as start-up drums. They were driven in by springs and locked into a full-in position. The other three control drums were used to bring the reactor up to critical and maintain a constant power level. The control drums' reactivity worth could be adjusted

by adding Be shims, approximately 2.54 cm thick, to the back of the control drums. All of these surfaces were anodized to provide them with a high emissivity level. The reflector assembly was designed to limit the Be temperature to less than 732°C.

The control drums used for fine control were driven by stepper motors. The actuators were eight pole reluctance motors which produced torque by the interaction of magnetic forces between stationary teeth on the fixed poles and the notched teeth cut into the cylindrical rotor (Ref. 34). The stator-pole tooth alignment was such that, as each pole was energized, the rotor teeth were in a position to provide maximum torque. While not energized, the rotor was held in place by a brake mechanism (Ref. 3).

The control drums were held in place by a pair of self-aligning, journal bearings. The bearing was held in a spherical cartridge. Contact surfaces between the ball and socket were coated with AL_2O_3 and then coated with a Mo disulfate base which acted as a dry film lubricant. The bearings were designed for operation at 621.1°C with an environmental pressure of 1.33 x 10^{-3} Pa or less (Ref. 37).

HEAT TRANSFER SYSTEM

The S8DR was tested without an energy conversion system. Heat was removed from the core using NaK as the working fluid. Eutectic NaK was the primary and secondary heat transfer medium. Final heat rejection was by means of an airblast heat exchanger. An electromagnetic pump was used to circulate the coolant (Ref. 35).

OPERATING HISTORY

The S8DR was operated via an automatic control system similar to the one to be used with the SNAP 8 flight system. The S8DR included complete flight-type control drive hardware. Testing was done in a vacuum chamber maintained at 10^{-5} torr. The test facility contained equipment to control test vault temperature, pressure and oxygen concentration within allowable limits. The reactor was installed with a vacuum chamber in a shielded pit below the vault floor. A vacuum of 10^{-5} torr or better was maintained within the chamber by two mechanical fore pumps and two oil diffusion pumps located in an equipment room adjacent to the test vault. All radioactive coolant NaK piping and equipment was located within the sealed vault. Backup power sources were provided to ensure there would not be a total loss of power at any time during testing (Ref. 39).

Testing began in June 1968 with an initial power output of 600 kWt and an outlet temperature of 704°C. After a thousand hours of testing, the reactor was boosted to 1 MW(t) for a total of 431 h. It was then returned to its initial operating level (Ref. 37).

Soon after testing began, anomalous oscillations were observed in the reactor power level and the outlet coolant temperature. The oscillations continued for the first 1500 h (Ref. 40). After the one megawatt run there was a noticeable increase in coolant activity and a greater reactivity loss rate, indicating ruptures in the fuel cladding.

Testing was shutdown in December 1969 after completing 7000 h. All of the flight sytstem components operated successfully without failure or degradation in performance. These include control drum bearings, actuators, position switches and the cable harness.

Upon postexamination of the S8DR core, it was found that 72 of the 211 fuel elements had cracked cladding tubes. The cladding cracks were typical of a stress-rupture phenomenon.

An investigation of the S8DR operating data indicated that the oscillatory behavior was due to the clustering of the fuel elements under a thermal gradient, followed by an abrupt declustering caused by the rehydriding of the fuel rod. The rehydriding process applied a force in the opposite direcion. The diffusion of H from hotter to colder regions of the fuel rod caused it to act as if it had a delayed, negative coefficient of thermal expansion. This was initially believed to be a stabilizing factor and prevent thermal clustering of the fuel, but the S8DR test and other out-of-core testing have shown that the particular set of time constants and material properties can result in an unstable, oscillatory condition (Ref. 40).

The following conclusions were drawn from the examination of the fuel elements:

a. The fuel element cladding ruptures were the result of excessive cladding strain caused by fuel swelling due to temperatures in excess of the design value.

b. The fuel growth exceeded design limits due to over-temperature fuel conditions in the core. This resulted from hydraulic maldistributions attributed to fuel element bowing/clustering patterns, greater than anticipated

coolant bypass flow near the core periphery and the detrimental effects of surge tank gas (which was entrained in the NaK coolant) on the fuel element-to-coolant heat transfer characteristics.

c. The Hastelloy N cladding material strain-to-rupture characteristics observed in S8DR were in good agreement with design values.

d. Excluding elements which sustained major damage (e.g., cracked elements), it appears that some measure of H barrier damage was incurred relatively early in life, particularly in the tube section of the fuel elements. The damage seems to have occurred primarily as the results of stresses caused by element-to-element loadings resulting from bowing/clustering of the elements.

e. The growth behavior of the Zr-H fuel material may be more temperature sensitive than previous data would indicate. The effect on S8DR of such increased sensitivity would have reduced full growth margins but cannot, per se, be ascribed as a prime contributing failure mechanism.

f. A statistical correlation was found that indicates that Cu impurity contents greater than 150 ppm in the fuel have the effect of reducing the fuel growth with respect to fuel containing lesser amounts of Cu when such fuels are subjected to essentially identical operating environments (Ref. 35).

CONCLUSION

The S8DR was the last reactor to be tested under the SNAP program. It was one of two reactors tested under the SNAP 8 program being developed as a power source for either a manned or unmanned application. It was concluded that design changes would have to be made to avoid cyclic clustering and declustering of the fuel elements. The advances made during the SNAP 8 program were used in conceptual design studies of space reactors.

IX. CONCEPTUAL SNAP 8 REACTOR DESIGNS

After the testing of the S8DR, the emphasis of the SNAP 8 programs went into the design of four conceptual reactors from between 1969 to 1971. The four reactor studies were the Zr-H reference reactor, the 5 kWe system, the Reactor Core Test and the Space Power Faculty Reactor.

Zr-H ADVANCED REACTOR

The Zr-H advanced reactor was designed specifically to be used in a manned mission with a 4 π shielding design (Fig. 16). The design objectives were 600 kWt power, an outlet temperature of 704°C and the ability to operate for over 20,000 h unattended. It was to use a SNAP 8 core design with slight changes, such as:

- using fins on the fuel elements,
- increasing the number of fuel elements to 295,
- use of Incolnel 800 or Hastelloy X for the cladding material.

The Zr-H reference reactor control drums were designed to minimize the 4 π shielding envelope of the system. The drums were smaller in diameter and designed to be cooled by the inlet NaK. They were to be fabricated from BeO which acted as a reflector and Ta-10 W which acted as poison. The reactivity was controlled by rotating the control drums which added poison or fuel.

The Zr-H reactor was designed to be compatible with more than one energy conversion system, depending upon the mission (Ref. 40). It was designed to meet system requirements for a 25 kWe thermoelectric power conversion system (Ref. 3).

5 kWe THERMOELECTRIC REACTOR SYSTEM

The 5 kWe reactor was being designed to produce from 1 to 10 kWe using the U-Zr SNAP reactor and a compact tubular lead telluride thermoelectric converter. The thermoelectric unit was being developed by Westinghouse Astronuclear Laboratory (Ref. 1). The 5 kWe reactor was designed to operate for 5 years for use in an unmanned mission.

The design objectives were:

- 5-year life;

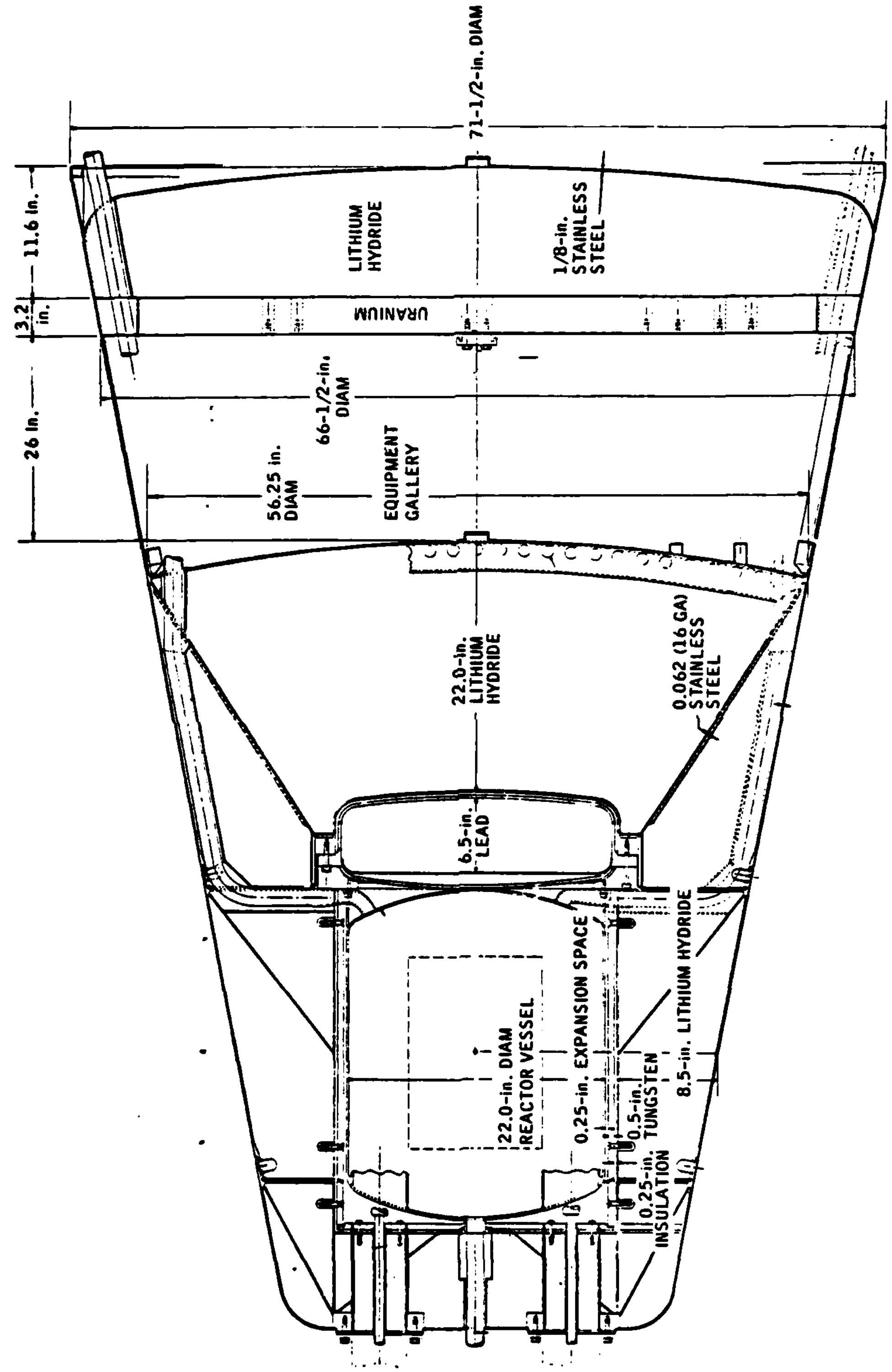

Figure 16. Zr-H reactor system (after Ref. 41).

- 5 kWe met unconditional power at the power system-spacecraft mating plane in a space environment at end-of-life;
- compatible with unmanned-type spacecraft and launch vehicles such as TITAN Class boost vehicles;
- radiation dose at the payload mating plant of 10^6, gamma and 10^{12} NVT, neutrons, average;
- use of Zr-H reactor and PbTe compact thermoelectric tubular technology, and
- automatic start-up and control capability (Ref. 28).

The 5 kWe reactor core was to be 26.67 cm in diameter by 40.64 cm long. A total of 85, 2.54 cm dia fuel pins, were to be used. Each fuel rod consisted of a segmented (5-piece) fuel rod of hydrided 10 percent U-Zr alloy, sealed within a Hastelloy X cladding tube. A burnable poison was included as a vapor-deposited coating of GdO, applied to the radial surfaces of the fuel slugs (Ref. 7).

Of the 85 fuel elements in the core assembly; 27 were finned in a left-hand direction, 27 in a right-hand direction and 31 were unfinned. The special fin design was incorporated to improve the reactors thermohydraulic performance.

The main difference of the 5 kWe system from the other Zr-H reactors was its reflector assembly. The reflector assembly was tapered and, instead of having rotating control drums, the reflector had vertical sliding control segments (Fig. 17). The reflector was 3.048 cm thick at the top of the reactor and 9.14 cm thick at the bottom. Two segments of the reflector assembly were designed to slide vertically to provide reactivity control. By lowering the segments, a 10.16 cm high window core midplane was opened which would decrease the reactivity (Ref. 42). Control actuators were used to monitor the reflectors position. The frustum shape of the reflector was chosen to minimize overall system weight (Ref. 43).

In choosing the optimum design, the basic requirement was that at operating conditions, portions of the movable control element must not protrude outside the cone. Protruding portions would cause radiation scatter on to the dose plane so the shield diameter would have to be increased. Three

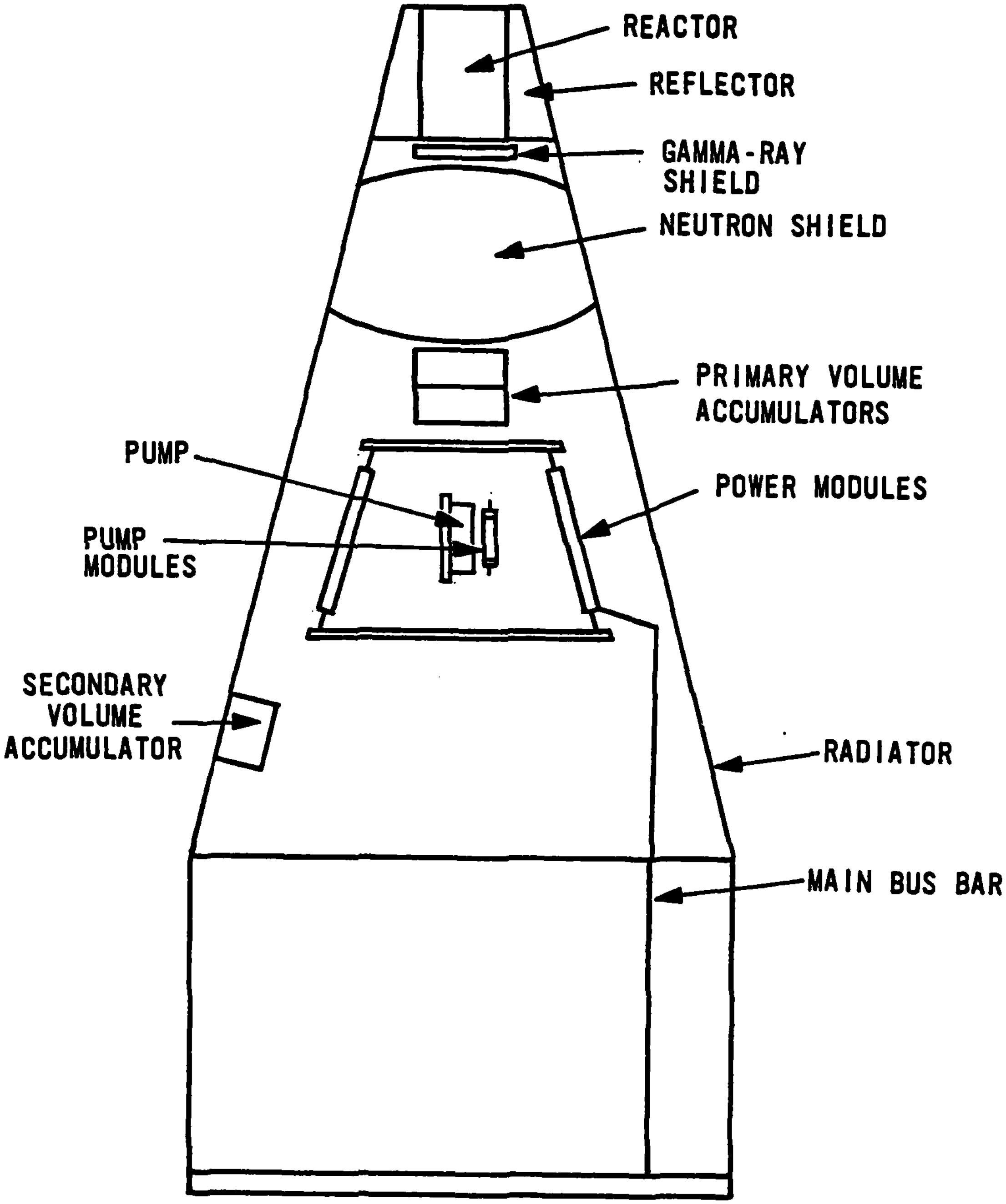

Figure 17. 5-kWe system schematic (after Ref. 7).

configurations were analyzed using the cone-shape reflector system. It was found that the sliding reflector resulted in a weight savings of around 45.6 kg or more over a rotating drum system (Ref. 43).

The 5 kWe reactor was never tested, but extensive preliminary work was completed. This work includes computer analysis, material testing and design.

The reactor core test was designed as a test reactor for the resolution of fuel element design problems that were outstanding after the S8DR operation. The Space Power Facility was designed for operation in conjunction with a NASA program for operation at the Plumbrook Space Power Facility. This reactor represented the last design effort in the SNAP 8 family of reactors (Ref. 7).

X. SNAP 10A

The SNAP 10A was a Zr-H reactor designed to produce a minimum of 500 We for up to 1 year or longer. It incorporated static/dynamic control and thermoelectric conversion systems.

The SNAP 10A was the only nuclear reactor the United States has actually flight tested. It was successfully launched on 3 April 1965 from Vandenberg AFB, California, and placed in a circular polar orbit. After 43 days of successful operation, the reactor was shutdown as the result of a high voltage failure sequence in the electrical system of the Agena spacecraft. The flight was considered successful, because the reactor was automatically brought up to operating level via ground command and operated as predicted from ground testing. Also, the SNAP 10A program confirmed that a space reactor could be safely transported and launched into orbit.

This reactor was also ground tested with a pseudoflight system which was operated in a simulated space environment. It was operated for 10,000 h without interruption before being shutdown for posttest examination. The SNAP 10A demonstrated the feasibility of the operation of a reactor in space. Although the power output is too low to meet the current needs, much of the technology and program knowledge gained from the SNAP 10A testing is relevant today.

FUEL ELEMENT DESIGN

The reactor core consisted of 37 fuel elements each 32.64 cm long and 3.17 cm in dia. The cladding was fabricated from Hastelloy N, with a wall thickness of 0.038 cm. The ends of the fuel element were sealed with end caps made of Hastelloy N and welded to the cladding tubes. The fuel was 31.11 cm long and 3.07 cm in dia. There was an axial gas gap of 0.0076 cm which was filled with H to promote heat transfer (Ref. 44). The cladding tubes were coated with a ceramic layer, Solaramic (S14-35A), which helped to prevent H leakage from the fuel element. The protective layer was from 2 to 4 mils thick. A burnable poison, Sm_2O_3, was added to the ceramic barrier to decrease the initial amount of reactivity. The reactor ran at a virtually steady-state power level without dynamic control.

The ceramic glass barrier was composed of a proprietary coating made from technical grade oxides, nitrates, and carbonates. It has a theoretical density of 3.1 g/cm^3 and an actual density of 2.8 g/cm^3. The ceramic coating was applied in three firings. In the last two firings a small quantity of SmO was incorporated in the coating. The nominal SmO loading was 3.1 + 0.3 mg/cm.

One end cap of the fuel element was welded to a cladding tube prior to application of the ceramic barrier. After the ceramic barrier was fired, a fuel rod was inserted into the cladding tube. The tube was then sealed against H loss by insertion of a ceramic coated blend cap. The H barrier was made complete by locally heating the cladding tube and blend cap to the ceramic surfaces together. Following the blending operation, an end cap was welded to the cladding tube, covering the blend cap (Ref. 45).

Each fuel pin was composed of approximately 128 g of U^{235}, 11.8 g of U^{238}, 24.6 g of H and 1215 g of Zr. A small amount of C was also used as a grain refiner. The total weight was approximately 1.38 kg of fuel material per fuel element. The U was fully enriched. The fuel was hydrided to an N_h of 6.35 x 10^{22} at/cm^3. All of the edges of the fuel were rounded to prevent damage to the ceramic barrier during assembly and handling of the fuel element.

Less than 10 of the 37 fuel elements had a nominal H content of 6.0 x 10^{22} at/cm^3 and/or a SM_2O_3 loading of 6.3 mg/cm. The special fuel rods were used to adjust the excess reactivity and passive control characteristics of the core (Ref. 46).

REACTOR CORE

A total of 37 fuel elements, arranged in a triangular array were used in the SNAP 10A. The fuel elements were set in a 3.2 cm center-to-center triangular spacing. Internal side reflectors of Be were used to round the hexagonal core configuration and to fill the voids between the fuel and the reactor vessel. The reactor vessel was fabricated from type 316 SS with an inside diameter of 22.54 cm, a length of 39.62 cm and a minimum wall thickness of 0.081 cm. A support ring, two NaK inlet pipes and support bracketry, all of which are fabricated from 316 SS, were welded to the reactor vessel.

The fuel elements were held in place by upper and lower grid plates. Top and bottom end pins 0.615 cm and 0.455 cm in diameter, were engaged in holes in the upper and lower grid plate (Ref. 47). Each plate was 22.22 cm in

diameter and fabricated from Hastelloy C. The upper plate was a solid piece of Hastelloy C which was 0.317 cm thick. The lower plate was a brazed assembly consisting of a 0.152 cm thick baffle plate and a 0.152 cm thick orifice plate with spacers between them. The overall thickness being 1.27 cm (Ref. 46). Each plate was perforated with 72 holes on a 1.85 cm triangular pitch for the coolant flow. The diameter of the flow holes in the orifice plate varied from 0.635 cm surrounding the central fuel elements and 0.477 cm at the perimeter holes. The lower grid plate was supported by a ring at the bottom of the reactor vessel and the top grid plate was spring-loaded against the vessel top head to allow for thermal expansion of the core in the axial direction (Ref. 42). A total of 12 springs were used, they were made of Rene 41 wire and each exerted a force 166.7 N. The free and compressed lengths were 1.53 and 1.27 cm, respectively (Ref. 46).

REACTOR REFLECTOR AND CONTROL SYSTEM

The SNAP 10A reactor was reflected by a layer of Be, approximately 5.08 cm thick, which surrounded the outside of the core. This layer was made up of plane sections approximating a cylinder. Four semicylindrical cavities, spaced 90 degrees apart were set in the Be reflector.

Four semicylindrical control drums were used for control of the reactor. They had a radius of 8.89 cm and a length of 25.72 cm. The control drums were used to regulate the amount of neutron leakage from the core, thereby controlling the reactor power level. The total weight of the reflector system was 46.8 kg.

The flight system was designed so that after the start-up command was received, squibs would be fired into actuators adjacent to each control drum, thereby, pulling the pin and releasing the drum. Two control drums were immediately inserted and the fine control drums would then be stepped in. The sudden insertion of the two coarse control drums would add $4.30 of reactivity. Fifty seconds after the start-up command, the two control drums would take their first step. The fine control drums then were stepped in a half a degree every 150 s. Criticality was then reached approximately 7 h after start-up. The rate of temperature and power increase during start-up was limited to ensure reactor stability. Recommendations were made to increase the

reactivity worth of the course control rods, so that the reactor could be made critical within 30 min rather than the 6 h required on SNAPSHOT (Ref. 48). Start-up would then be limited by the thermal stress criteria, rather than reactor stability. Control was to be linked to the NaK outlet temperature. When the NaK outlet temperature dropped below an established point, the fine control drums would take another step inward. This would continue for 72 h after the start-up command, at which time all dynamic movement was ended (Ref. 49). The reactor then ran at steady-state power without dynamic control. The SNAP 10A possessed a strong negative temperature coefficient which was used for inherent control and stability over the operating lifetime (Ref. 50).

The control drum actuator's motor was designed so that it rotated in finite steps. These drums were linked to the actuator by two gears. The pinion gear attached to the motor shaft was made of Haynes Stellite 6B, and the gear segment attached to the drums was made of a Ti alloy. A coat of an Alpha Molybote X-15 was used to prevent self-welding of the gears (Ref. 36).

The reflector/control assembly was fabricated in two halves (Fig. 18). Each control drum rotated on a pair of self-aligning bearings--the upper was a radial bearing and the lower was a radial-thrust bearing (Ref. 51). A retaining band was used to hold the two reflector halves together. This band was held off from the reflector by flexible graphite blocks to prevent self-welding. A gap between the reflector system and the core vessel was maintained to ensure that they would not self-weld.

The reactor system could be shutdown by the ejection of the reflector assembly. The reflector ejection would take place if one of three signals were given: (a) a ground command through an umbilical prior to lift-off, (b) telemetry or (c) a failure sensing device.

The failure-sensing device was sensitive to low converter output voltage. If the failure sensing device was actuated, a 1 min timer was started. If the signal was a minor fluctuation and the system returned to normal, the timer would reset. If not, a 1 h delay time would be started which would trigger an electrically actuated band release device if the command was not cancelled (Ref. 47).

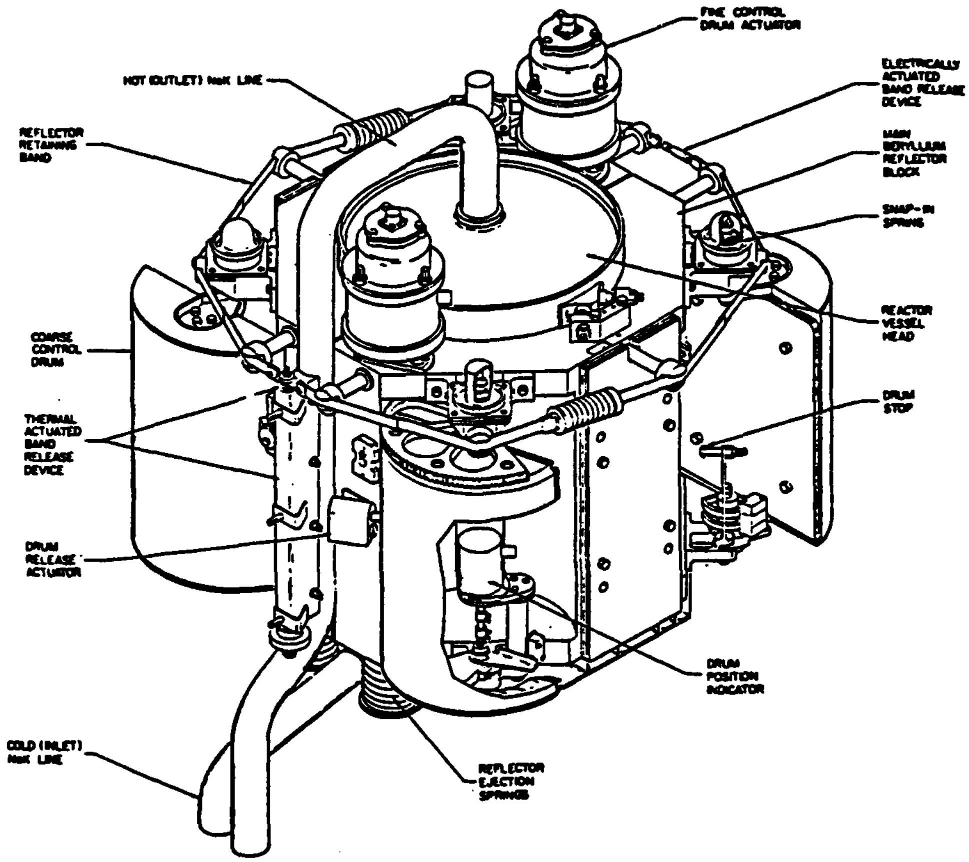

Figure 18. Control and reflector assembly (after Ref. 7).

The band release device was a hollow cylinder fabricated from Rene 41 which contained an electrical heater, the total length being 5.8 cm which included band end fittings. The band release device was an integral part of the reflector retaining band which caused it to break by applying heat. The heater consisted of 32 Ga W wires coiled around a ceramic bobbin and placed within the cylinder.

When the retaining band breaks, it causes the reflector halves to fall away from the reactor and cause immediate shutdown of the reactor. Ejection is accomplished by compression springs located at the bottom of the reflector halves. When the retaining band is released, the reflector halves are pivoted outward by the spring force (Ref. 47).

A second band release device is also provided to separate the reflector retaining band. It is actuated by a drop in the NaK outlet temperature. A steel rod is mated with a Mo tube, they are rigidly jointed at one end by a notched stud, which also serves as a shear pin between two overlapping, end-fittings of the reflector retaining band and bolt. If the temperaure of the coolant goes below a specified value, the difference in thermal expansion of the stainless steel and Mo will cause the stud to break, thereby, releasing the retaining band (Ref. 47).

The retaining band is also designed to release upon reentry heating. This ensures that the reflector assembly will be rejected before impact and allow dispersion of the fuel elements from the core.

HEAT TRANSFER AND POWER CONVERSION SYSTEM

A NaK alloy was used as coolant for the SNAP 10A. The coolant outlet temperature was 543.3°C. The NaK was circulated through the core and thermoelectric converters by means of a liquid metal d.c. conduction-type pump. The pump was powered by its own lead-tin-telluride (PbSnTe) theremoelectric converters. The PbTe N and PbSnTe P were chosen on the basis of high figure merit at the operating temperature relative to other materials. The pump was designed to produce a minimum of 831 cm^3/s of NaK flow at 565.5°C against a head of 0.091 kg/cm^3.

The PbTe thermoelectric elements were initially to be used on the SNAP 10A power conversion system, they were considered advantages because they had a high performance level and had been used extensively in other applications.

Three distinct disadvantages were known: (1) high sublimation rates at operating temperatures, (2) low strength and brittle mechanical behavior and (3) lack of a contacting material and contacting process that would meet the SNAP 10A requirements (Ref. 52).

In 1961, P and N-type thermoelectric SiGe alloys were developed by the RCA Princeton Research Laboratories. Although they have lower performance than PbTe, they are advantageous in that they have (1) lower vapor pressure at high temperature (2) good mechanical integrity and (3) stability at temperatures greater than those required by the SNAP 10A (Ref. 3). The SiGe thermoelectric were also chosen for the SNAP 10A because of their predicted growth potential.

The power conversion system consisted of N and P doped SiGe thermoelectric materials, thermally coupled but electrically isolated from the NaK heat transfer medium (Fig. 19) (Ref. 34). A total of 2880 pellets were electrically connected in two parallel paths by Cu straps at the hot end of the pellet and Al radiator platelets at the cold end (Ref. 54). They were bonded onto the radiator surface. The radiator consisted of 40 SS tubes arranged in a conical configuration. The heat was transferred from the NaK tube through a thin alumina disc, which was used as insulation, then to the SiGe pellets to an individual Al radiator. The total effective *radiator* area was 5.8 m^2 (Ref. 50). The TE system was designed to operate at a hot junction temperature of 573°C with a maximum of 593°C. They were limited as a result of the increase in electrical contact resistance between the SiGe pellet and the W shoe (Ref. 44).

Ground testing of the thermoelectric system was done in a simulated space environment. Degradation of the power output was observed and this was attributed to the disposition of carbonaceous material on the module insulators. This carbon resulted from the outgassing of the electrical insulation, particularly that which was hot, in the case of the system tests and from vacuum pump oil contamination, in the case of module tests (Ref. 53).

The NaK tubes were fabricated from 405 SS, the electrical insulator of alumina, the hot strap material of Cu, the compensator and element shoe of W and the fin material of Al (Fig. 20). All materials were brazed or otherwise metallurgically bonded together. During the FSM-1, nonnuclear testing, it was established that the estimated degradation rate was 4 percent for 1 year of operation (Ref. 30). The total power output was to be 500 W or more.

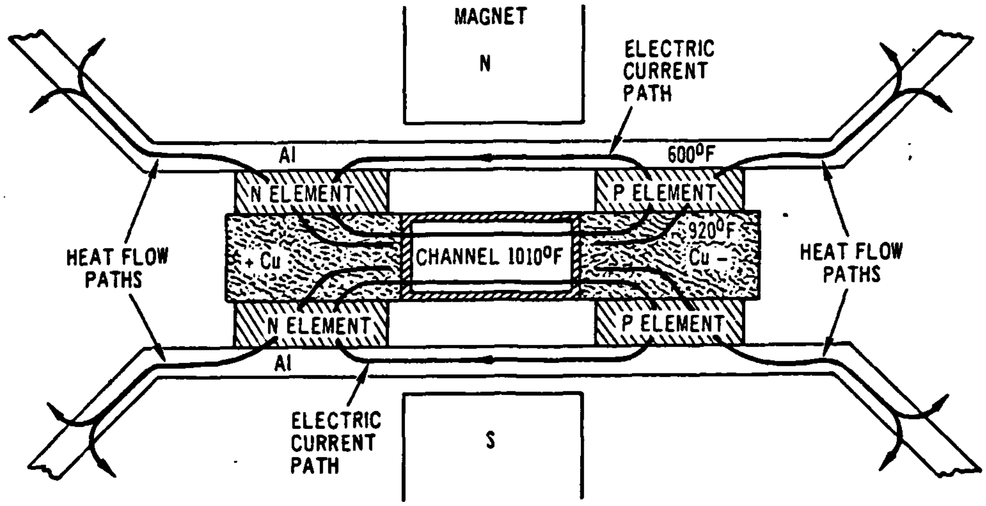

Figure 19. SNAP 10A thermoelectric pump configuration schematic (after Ref. 52).

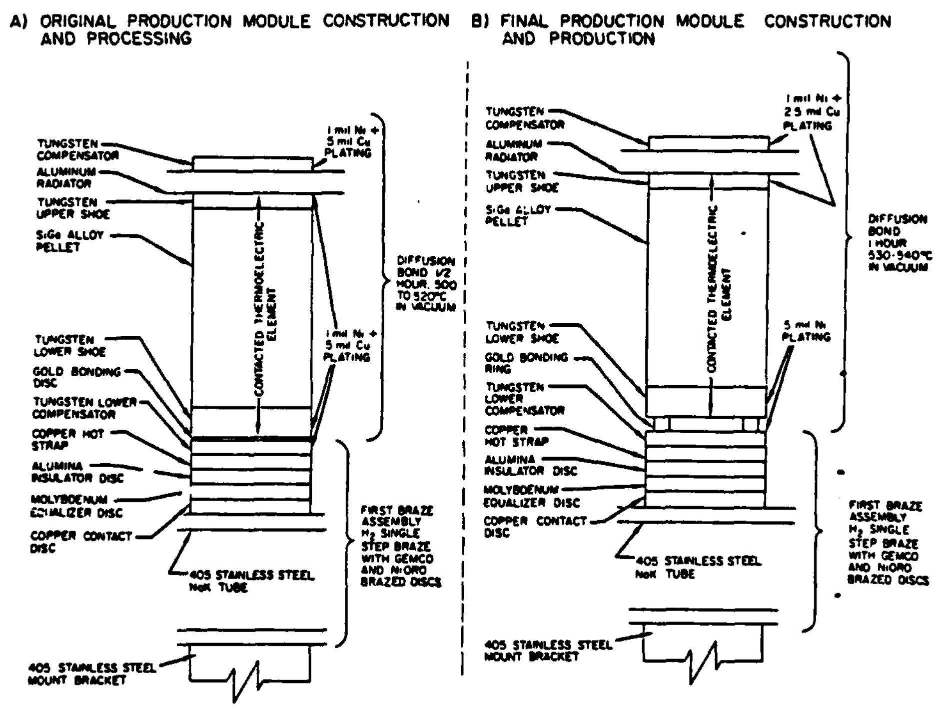

Figure 20. Construction of SNAP 10A thermoelectric converter (after Ref. 52).

To ensure the NaK would not freeze and cause plugging in the system, it was kept above 32.4°C during prelaunch, launch and prestart-up of the nuclear reactor in orbit. The NaK was loaded into the system at 38°C before launch. Three techniques were used to ensure the NaK would not freeze: (a) an ejectable heat shield with emissivity coatings designed to effect a net heat input into the system and (b) the inherent heat capacity of the system and (c) an induced low flow of the NaK to provide a more uniform temperature distribution (Ref. 44). Two Cu electrodes were placed on the pump throat to accept an auxiliary current supply of about 40 A to maintain the required 3 percent flow prior to start-up of the system. During the actual flight, the flow was 7 percent of full flow which was nearly double the design requirement. The thermoelectric pump contributed half the flow and the auxiliary power source the other half.

Bellow type expansion compensators attached to the return legs were used to ensure a relatively constant pressure of 2.41 kPa. This was to ensure that the NaK would remain void free and to prevent cavitation in the pump (Ref. 44 and 46). The bellows were restrained from moving during launch to prevent overstressing by a locking device. In the event of a lock-release failure of one unit, the second bellows assembly was capable of absorbing the full net expansion of the NaK without exceeding the maximum allowable pressure.

The SNAP 10A structure was fabricated from Ti, 20 mil thick, formed into a corrugated cone. The structure transferred the reactor shield loads to the spacecraft and directly supported the thermoelectric conversion system (Ref. 48 and 53). The reactor was supported on the converter structure by four support legs formed from 0.081 cm 6AL-4V Ti alloy. The support legs were designed to support the entire structure during launch loads, and were attached to the reactor and converter structure with blind bolts (Ref. 47).

SHIELDING

The SNAP 10A system had a shadow shield designed to keep the dose rate under specified values at the reference dose plane. The shield assembly was located directly beneath the reactor and weighed 98.6 kg. The shield was fabricated from a cold pressed LiH shielding material reinforced with stainless steel and contained in a stainless steel casing. The honeycomb

design was used to minimize crack propagation and to hold the LiH block together when subjected to thermal gradients (Ref. 47). A specific gamma shield for the SNAP 10A was unnecessary. During SNAPSHOT the measured gamma dose rate at the reference dose was 7×10^5 r/yr compared to the design objective of 1×10^7 r/yr (Ref. 53). A set of eight spring assemblies attached to the shield casing and to a parabolic plate below the shield were used as support. To position the LiH against the forward end of the launch phase, a spring-support mechanism preloads the hydride to the anticipated vertical acceleration load during launch. The casing length was approximately 81.28 cm and the LiH length was 69.77 cm. The maximum and minimum shield diameters were 53.65 cm and 20.10 cm, respectively (Ref. 47).

The shield was designed to limit the total reactor integrated nuclear radiation to less than 4×10^7 R of gamma radiation and 5×10^{12} n/cm^2 neutron energies of 1.0 MeV at any point on the dose plane (Ref. 55). The reference dose plane was 152 cm in diameter located 533.4 cm below the reactor core.

SNAP 10A TEST HISTORY

During the SNAP 10 program a total of eight prototype and qualification systems were built and tested. Three were used for structural tests, three were prototype thermal vacuum performance tests, two were final complete system qualification models and the final flight system. The two qualification systems consisted of a nuclear system and a nonnuclear unit which used an electrical heater to simulate the reactor core, both of which used flight hardware (Ref. 48).

NONNUCLEAR THERMAL TESTS (PSM-3)

The PSM-3 was the first prototype system to be tested under the SNAP 10A program. Testing was done to explore thermal, hydraulic and heat transfer characteristics (Ref. 43). An electric heater was used to simulate the nuclear heat source, also the system utilized a partial PbTe converter instead of the SiGe thermoelectrics which were used on the flight system.

Testing was done in a vacuum of 10^{-3} mm Hg and a cold wall heat-rejection sink temperature between 4°C and 65.5°C. Detailed thermal behavior of the system in orbit prior to reactor start-up was experimentally verified by local liquid nitrogen cold plates and a gross simulation by infrared lamps of the solar heating and shade effects (Ref. 53).

Over 1000 h of testing was accomplished with this system at operating temperatures between 93°C and 482°C during the time period April 10 and October 12, 1962. Valuable information was obtained from the initial thermal testing and changes were made on the following test of a full-scale, non-nuclear system (FSM-1).

SNAP 10A FLIGHT SYSTEM PROTOTYPE (FSM-1)

The SNAP 10A flight system prototype was full-scale, nonnuclear mock-up with a special heating unit to simulate the reactor heat source. Testing was conducted from September 8, 1963 to January 16, 1964. The FSM-1 was tested to simulate conditions from ground launch to nuclear start-up in earth orbit (Ref. 56). All testing was done in a vacuum environment.

Testing was begun with a simulated prestart-up orbital test, including a thermal and nuclear checkout. Operation then began on a 90 day full-power test with an average outlet temperature of 493°C and average power output of 400 We.

The thermoelectric power converter, coolant volume expansion compensator, thermoelectric d.c. conduction pump, and instrument assemblies were of developmental flight design. Whereas the Ti support structure was of qualified flight design.

SNAP 10A FSM-4

The flight system mockup number four (FSM-4) was a nonnuclear test system duplicated in every detail to that of the flight system except for the nuclear heat source (Fig. 21). A special heating unit was used to simulate the reactor as a heat source. It was the only test system to be loaded with NaK and thermal performance tested at both acceptance and qualification levels (Ref. 57). The FSM-4 was a prenuclear test to demonstrate successful start-up in surviving the initial temperature transient.

The FSM-4 was tested in the same facilities used by FSM-1. The system was tested in a vacuum environment. The test facility was insulated with panels in which cryogenic fluid was circulated to simulate the thermal environment of space.

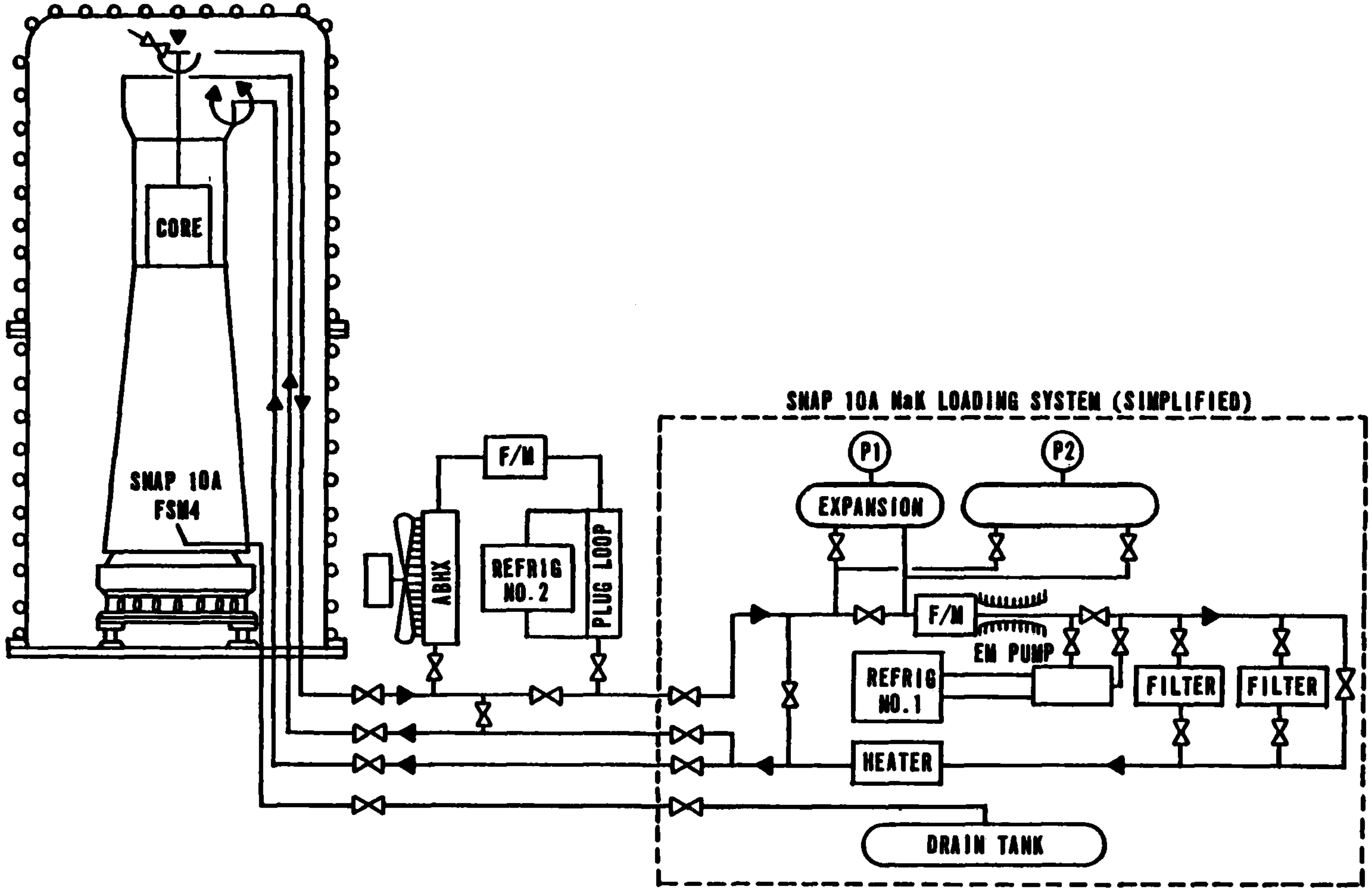

Figure 21. SNAP 10A ground demonstration test (after Ref. 53).

The main four objectives in testing of the FSM-4 include:

- shock and vibration testing of a NaK loaded system,
- simulated orbital operation before start-up,
- simulated orbital start-up sequence with emphasis on the thermal transient, and
- thermal reference endurance testing (Ref. 57).

Testing demonstrated that the flight system would produce rated power after being subjected to the launch and orbital environment. The endurance indicated problem areas in degradation of the electrical output via shorting of the converter insulators which resulted in an expenditure of effort to determine the cause of this degradation and to redesign the system (Ref. 53).

SNAP 10A/AGENA COMPATIBILITY TESTING

To ensure mechanical and electrical compatibility with the Agena D vehicle an electrical mockup, the FSEM-2, was mated to the Agena D functional metal mockup. The FSEM-2 system had electrical and instrumentation mounted on a complete structure; however the reactor, coolant system, power conversion unit, and radiation shield were simulated by mass mockups to duplicate the weight and handling characteristics of the flight unit (Ref. 53).

The FSEM-2 was the first system to test the compatibility of the electrical system with the Agena vehicle, several problems were identified which led to changes in the flight design. The system was later rewired and flight qualified equipment added, the new design was named the FSEM-2A. The system was subjected to shock, vibration, acceleration, temperature, vacuum conditions simulating flight environmental conditions and initial investigation of electromagnetic interference.

The final compatibility testing was done on the FSEM-3. Testing was conducted at LMSC's Sunnyvale facility between May 1964 and February 1965. Compatibility tests consisted of programming the two mockups through a simulated flight sequence of events with the main unregulated power bus maintained at either 23.5 or 28 Vdc.

A significant amount of information was obtained from the SNAP 10A electrical mockup testing. Several changes were made in the system before being flight qualified.

SNAP 10A GROUND QUALIFICATION SYSTEM

The SNAP 10A nuclear ground test, designated the S10F-3, was identical to the flight tested SNAP 10A including its structure, shield, PCS, and expansion compensators with minor modifications to accommodate for ground safety.

The reactor system was brought up to full power on 22 January 1965 with final shutdown on 15 March 1966. The system had over 10,000 h of uninterrupted operation. It was operated at 35 kW thermal for 390 days and then raised to 44 kWt after receiving permission from the AEC. Active control was employed for first 3 days after the raise in power followed by 25 days of static control (Ref. 53).

At the end of 1 year, the outlet temperature had decreased greater than predicted. This was mainly attributed to the continuing H redistribution, but other system uncertainties affected the reactivity performance also. It was determined that the H redistribution effect was essentially completed during the active control period for high temperature reactors, and that all other uncertainties were reduced due to the strong dependency of the H to redistribute at high temperatures.

Another important conclusion was that the FS-4 reactor temperature drift was almost the same as the flight tested SNAP 10A. This verified that the behavior of statically controlled SNAP reactors could be predicted based on prototype ground testing.

SNAP 10A FLIGHT TEST

The SNAP 10A flight system, FS-3, was launched 3 April 1965 from Vandenberg AFB into a circular polar orbit (Fig. 22). The system operated successfully for 43 days when it shut down due to failure of the voltage regulator on board the Agena spacecraft. Although secondary payloads were included on the SNAPSHOT launch, the main purpose for the flight was to observe the behavior of the SNAP 10A in space.

The complete SNAP 10A system had an overall height of 347.9 cm and a mounting base diameter of 127 cm. The total weight of the system was 436.4 kg, 100 kg for the radiation shield and 22.7 kg of diagnostic instrumentation (Fig. 23) (Ref. 54).

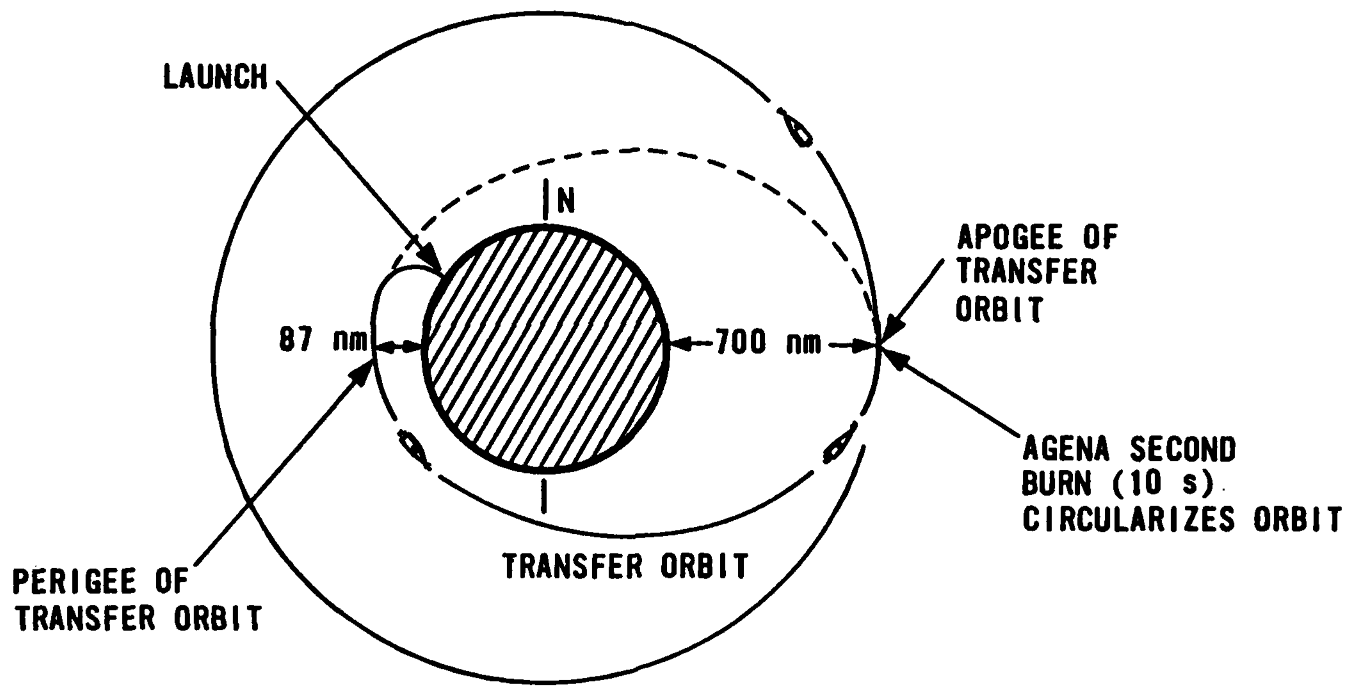

Figure 22. SNAPSHOT launch and transfer orbit (after Ref. 54).

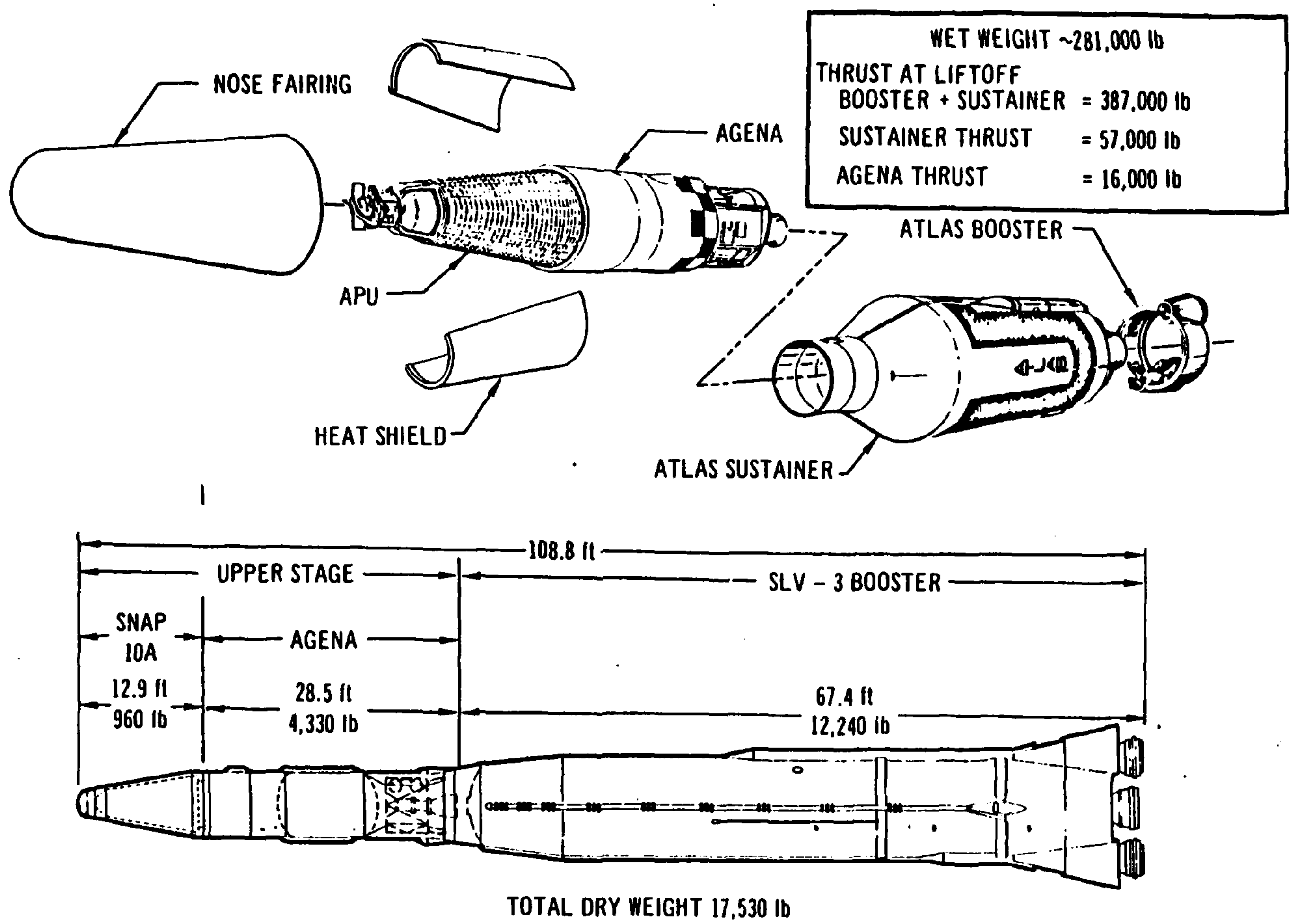

Figure 23. SNAP 10A/Agena/Atlas vehicle configuration (after Ref. 54).

The flight system used the SNAP 10A reactor design outlined earlier. The FS-4 included an instrumentation compartment which housed the start-up and control system, diagnostic instrumentation and electrical connections which were used to mate the reactor system with the Agena (Ref. 48).

Preflight testing included the following:

- Fabrication completed 17 September 1964.
- Acceptance-level shock and vibration tests successfully passed 24 September 1964.
- Fuel loading and dry critical testing completed 26 October 1964.
- NaK loading and thermal reference testing completed 15 January 1965. (Using electric heaters to simulate the heat source.)
- System shipped to VAFB 18 February 1965.
- System checked out and mated to Atlas-Agena on 2 April 1965.

During launch the reactor was protected by a nose fairing which was ejected at the end of the Atlas boost phase. An ejectable heat shield which covered the thermoelectric converters was used to ensure that the liquid metal coolant would not freeze and was ejected when the coolant temperature reached 48.9°C. The shield was released by pyrotechnics and ejected from the radiator by preloaded springs.

The SNAP 10A was mated to the forward end of the Agena by a payload adapter. The Agena vehicle provided the essential power distribution system, tracking and command system, control system and voltage regulation (Fig. 24). The SNAP 10A and Agena were designed to operate as a single integrated spacecraft (Ref. 54).

An Atlas-Agena vehicle was used to boost the reactor up to orbit. The Atlas booster and sustainer separated and the Agena was used to place the system into orbit.

One of the secondary payloads was a Cs-fueled ion engine which was designed to produce approximately 0.0089 to 0.0131 N of thrust along the vehicles neutral axis, where it would produce no force to alter vehicle attitude. The system was intended to demonstrate the cyclic operation of the engine in space for an extended period, to compare with laboratory testing and demonstrate compatibility with the reactor system and the Agena (Ref. 53).

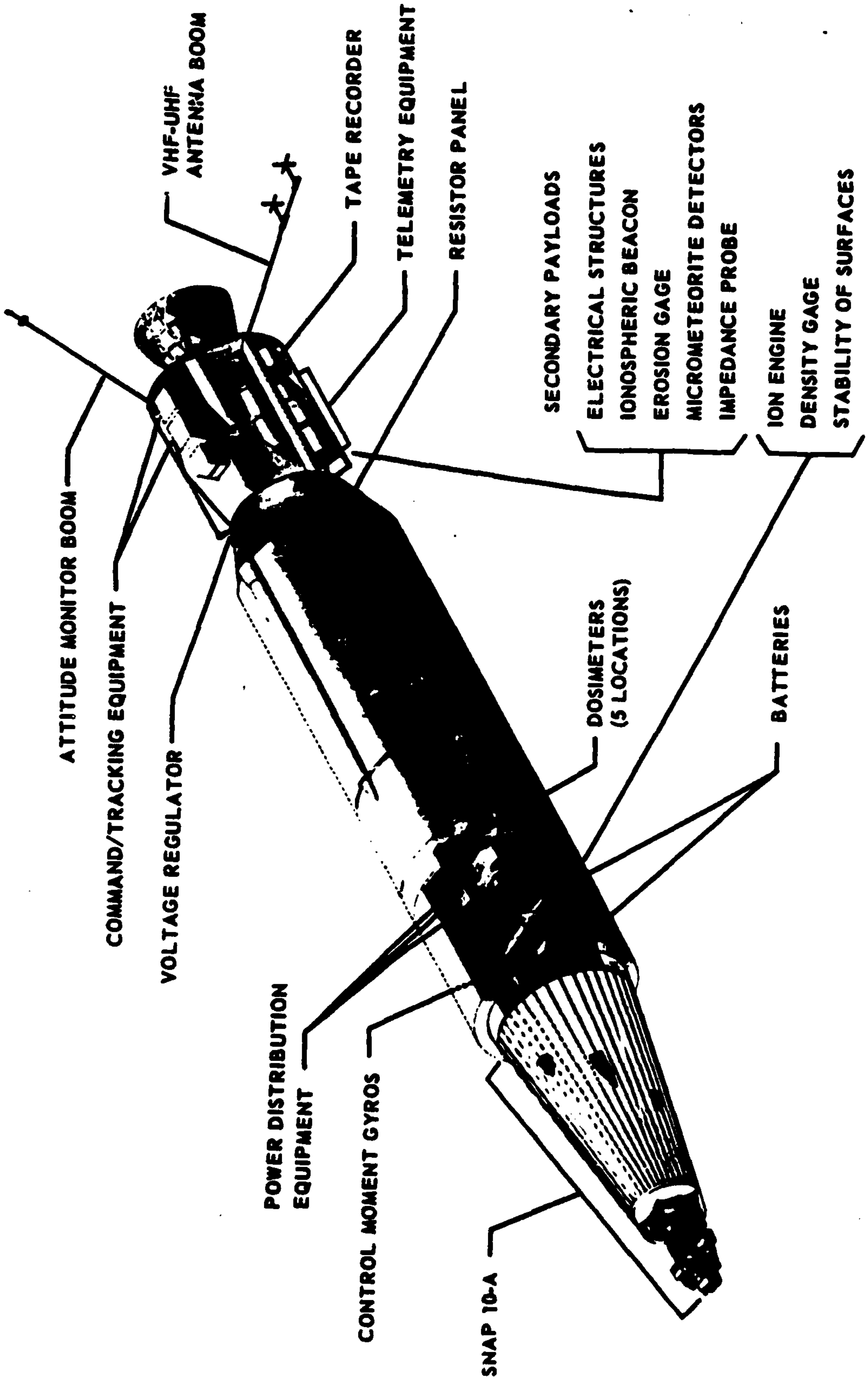

Figure 24. Spacecraft configuration (on orbit) (after Ref. 58).

The ion engine was to operate from its own secondary batteries, where excess nuclear power output was used to recharge these batteries after each ion thruster operation.

A total of eight research experiments were on the vehicle at launch. These were provided by AF Cambridge Research Laboratories (AFCRL), AF Space Systems Division (AFSSD) and Army (Ref. 58). These eight payloads were as follows:

a. AFCRL

- Micrometeorite detector (grid)
- Micrometeorite detector (membrane)
- Electrical structures
- Density gauge
- Erosion detector
- Impedance probe

b. AFSSD

- Stability of surfaces

c. Army

- SECOR

Prior to launch, the 5-MC side of the impedance probe was inoperative, but all other experiments were functioning normally. The secondary payloads were energized on revolution 21 for total recording on the Link 3 tape recorder. The SECOR was ejected during revolution 0 and the other experiments were kept energized almost continuously following revolution 23 to absorb the power that would normally have been used to charge the ion engine battery (Ref. 58). Two of the experiments failed. The micrometerorite (membrane) detector failed before data were even taken, and one complete unit (of two provided) of the stability of surfaces experiment failed between revolutions 192 and 243 during which time Link 3 tape recorder was not enabled (Ref. 58). Information on the experimental results can be found in Reference 60.

The reactor began operation after receiving a special coded command from ground command. The start-up command was given 3.7 h after launch. Once initiated the four drum locking pins were released and power was applied to the start-up command. The two course control drums were immediately inserted to their full-in position and the fine control drums were step-wise inserted, criticality was reached within 6 h after receiving the start-up command.

The active control phase lasted for 154 h after the initial start-up. During the active control period the reactor system did not reach steady state because of the change in reactivity following each drum step insertion. During this phase the operation of the ion engine caused electromagnetic interference, upsetting the attitude control and, therefore, the vehicle stability causing the vehicle to slew severely. The source of the electromagnetic interference has been attributed to cycling off and on of the high voltage supply due to overload condition caused by contamination and arcing at the high voltage terminals of the Cs ion thruster (Ref. 48). Much of the telemetry data was unintelligible. The ion engine was shut-off until the effects of the problem could be better understood. The decision not to operate the ion engine meant that its batteries did not require recharging, thus reducing vehicle power demand by a maximum of 100 W (Ref. 48). The malfunction and failure sensing systems which had to be initiated by ground control were not activated because of the possibility the ion engine could cause the other systems to malfunction. The Link 2 tape recorder, which was used to detect drum steps between acquisitions was shut-off after orbit #39, because of the rate of deterioration of the tape.

After 600 to 700 h at full power, a faster than expected decrease in converter isolation resistance became apparent. The gross electrical power output was close to that expected, but the net power was decreased by 10 W lost to ground.

It was concluded that the degradation of FS-4 isolation resistance was due to deposition on the individual alumina insulators of hydrocarbons from insulating materials used in the instrument compartment and the Agena. Also, the high temperature wire inside the supporting structure tended to outgas at operating temperatures in the hard space vacuum (Ref. 53).

On May 16, during its 555 orbit, contact with the spacecraft was lost. Communication was regained 40 h later in orbit 574. "The telemetry data revealed a vehicle status inconsistent with any logical mode of operation of the malfunction and failure detection system, failure of a number of independent electrical components and a number of operations which could only be explained by ground commands that hadn't been sent." (Ref. 48).

The reflectors had been ejected away from the reactor (yet still connected to the system by the actuator cables) resulting in zero power output. The spacecraft was operating from the failure battery supply. The command system was inoperative, the redundant 115 Vac-power system was dead which resulted in the loss of control movement gyros attitude control system and about half the telemetry data. On May 21 during orbit 616 the failure batteries were depleted and telemetry transmission ceased.

The reason for the unexpected shutdown was analyzed by AI and LMSC, the conclusions reached after examining information received from SNAPSHOT and ground testing of the electrical system are as follows:

(a) The failure was unexpected, i.e., impending trouble was not indicated by prefailure telemetry data.

(b) The most plausible cause of shutdown is spurious commanding which resulted from a high voltage failure of the command decoder.

(c) The probable cause of the command decoder failure is high system bus voltage due to:

- A piece-part failure in the voltage regulator; or
- overstressing of the voltage regulator caused by reduced vehicle loads, or controller operation resulting in increased reactor power output.

(d) The initial malfunction cannot be determined.

(e) Principal equipment damage noted was most probably due to high voltage.

(f) All data anomalies can be credibly explained by a high voltage condition.

(g) The failure batteries were probably connected to the bus by a spurious command and not as the result of a low-voltage malfunction sequence.

(h) The thermal and radiation environment was not a significant factor in the shutdown.

(i) The possibility of collision, explosion, or other catastrophe is not supported by the data.

(j) The flight anomalied noted (ion engine interference with telemetry and vehicle attitude, and the decline of thermoelectric converter resistance to ground) were not factors in the shutdown (Ref. 58).

The SNAP 10A is currently in its initial 4000 year orbit. The SNAPSHOT flight test was valuable in that it demonstrated the feasibility of the operation of a reactor in space. Valuable information on the characteristics of space operation were also recorded, these include the fluctuation in power as it went from the sun's view to the earth's shadow, the effectiveness of the radiation shield, the performance of the electromagnetic pump and expansion compensators, the neutron source strength obtainable in earth's orbit from proton and alpha-n reactions and the interaction of the EM pump and the converter current with the earth's magnetic field.

Final recommendations intended to simplify and improve operation and to increase the amount of information available from the spacecraft is as follows (Ref. 40):

(a) Future tests of reactor powered satellites should incorporate more accelerometer instrumentation. Because these payloads (with their heavy lumped reactor and shield masses) are configured differently from other satellites, there is no body of directly comparable flight test data from which structural design criteria may be derived.

(b) Launch pad preheating of the SNAP 10A unit was a significant contributor to the stable NaK temperature and high flow during prestart-up. This procedure should be continued on future flights. The requirement for batteries to supply current to the pump during prestart-up can be eliminated with preheating.

(c) The inherent stability of SNAP reactors has been thoroughly demonstrated; the rate of temperature and power increase during start-up should be limited by thermal stress criteria rather than reactor stability criteria. There is no requirement for the long time delay between the beginning of start-up and criticality or between the initial power transient and full power.

(d) The control system temperature sensor should be redesigned so that it can be mounted in better thermal contact with the NaK, or it should be replaced by a current sensor. Either change would simplify calibration procedures, decrease control system response time, and simplify or eliminate NaK tube penetrations. The time required for reactor start-up should be reduced; insertion of the coarse control elements should decrease subcriticality enough that the reactor can be made critical within 30 min rather than the 6 h required on SNAPSHOT. The use of ground commands in controlling the system can be given more serious consideration where simplification is desired.

(e) Payload radiation doses in the Agena aft rack can be reduced to 1×10^{11} NVt/yr which will allow the use of unhardened, off-the-shelf electronic equipment. This could be accomplished by local shielding. On more advanced systems an improved shield (similar to that used on SNAP 2 and SNAP 8) together with a tapered reflector, could be used to reduce neutron scattering.

(f) Advanced system designs could resolve the diffculty of removing all gas during NaK loading by minimizing entrapment areas and establishing toleration amounts. One of the factors which should be considered in designing facilities is elimination of gas from the SNAP system.

(g) Instrumentation for any future system should taken into account the differing requirements of realtime and off-line analysis, and normal and anomolous operation.

(h) The malfunction and failure circuits should be redesigned to provide 1/ increased operational flexibility by separation of diagnostic and automatic reactor shutdown functions; 2/ ability to enable and disable the automatic shutdown functions; and 3/ high voltage detection. Redundancy of telemetry tape recorders, failure power supplies, and critical parameter instrumentation should be increased. Backup protection against high voltage, resulting from voltage regulator failure, and increased design against overvoltage in vital control and instrumentation equipment should be provided throughout the entire spacecraft.

(i) Tests and/or analyses of the voltage regulator should be performed prior to a second flight test to better define the conditions which overstress individual regulator components. An attempt should be made to eliminate the bias errors on individual telemetry channels by precise end-to-end calibrations. An investigation of the causes of the lower noise levels and higher accuracies of the 5 and 20 mV submultiplexers compared to the 50 mV sub and main multiplexers could lead to improvements in the accuracy of future telemetry systems. The tape recorder provided valuable information for engineering analysis and explained several apparent performance anomalies during SNAPSHOT; providing its reliability can be improved, the recorder should be used routinely on future flights as well as for malfunction-failure situations.

(j) The type and causes of telemetry errors observed on SNAPSHOT should be taken into account when selecting instrumentation for future flights.

(k) An experiment to measure the change in thermal emittance and solar absorption of SNAP 10A thermal control surfaces in space (similar to that which failed on SNAPSHOT) should be included on a future flight test. Alternatively, more accurate system radiator temperature measurements taken over complete orbits could serve the same purpose on surfaces at operating temperatures, though probably not as accurately.

(l) Sun/shade effects at full power were small, but not negligible. The effect of sun/shade on both power output and instrumentation performance should be considered in the design of future systems to assure that they will continue to be small.

(m) The effect of magnetic torques on spacecraft attitude control should be considered early in the design of future systems so that the pumps can be located and oriented to provide countertorquing, if required.

(n) SNAPSHOT provided information which not only indicated a number of ways in which future reactor or thermoelectric space power systems could be improved, but also demonstrated the adequacy of the SNAP 10A design and test program. Thus SNAP 10A and SNAPSHOT provided a firm, proven basis for the design, fabrication and test of more advanced systems (Ref. 48).

The SNAP 10A reactor system performed as expected and did not greatly deviate from the ground test results as extrapolated for space. The failure of the flight test was not related to the reactor system, but to the voltage regulator on board the Agena. The safety program developed for the SNAPSHOT program

has valuable information which can be applied to the current space reactor program. This includes information on system testing preflight evaluation, reactor transportation, launch pad procedures and flight precautions. Every step must be carefully safeguarded to ensure that no radioactive material is released, or that the system does not go critical before it is in a safe orbit.

XI. SNAP 50

The SNAP 50 was a fast reactor with a power output of 300 kWe which could be upgraded to 1000 kWe. Lithium was used as the reactor coolant. The Cb alloys were to be used for all areas in contact with Li and all high temperature regions, such as the pressure vessel, core support structure and fuel element cladding. The support structure which would be subjected to temperatures under 574°C, was to be made from Ti alloys. The UC and UN fuel alloys were both being considered as fuel choices, with the emphasis on the UN due to the good results obtained from in-pile fuel irradiation test (Ref. 60).

The Li coolant entered and exited the pressure vessel at the lower head. Thereby, cooling the core boundary and pressure vessel before entering the core from the upper plenum.

Six pivoted reflector segments were to be used for reactor control which completely surrounded the core. Each reflector consisted of a Cb alloy container filled with blocks of BeO. Each reflector was to be connected to the reactor and support structure by flexure bearings at each end, and driven by a colinear drive, d.c. stepping motor with a harmonic gear reducing unit. The reflector drive motor was located behind the shield, being connected to the reflectors by shafts which penetrated the shield. The reflector drive motor was operational at 672 K with drive torque of about 0.388 Nm. Steady-state control was to be dependent upon the reactor coolant outlet temperature.

POWER CONVERSION SYSTEM

A Rankine cycle energy conversion system with K working fluid was to be used as the power conversion system for the SNAP 50 (Fig. 25). A direct and indirect cycle were both being considered. The direct system had the advantage of a weight savings of 1.82 kg/kWe, whereas the indirect system was more reliable (Table 9). Schematics of the direct and indirect power conversion systems are shown in Figure 26.

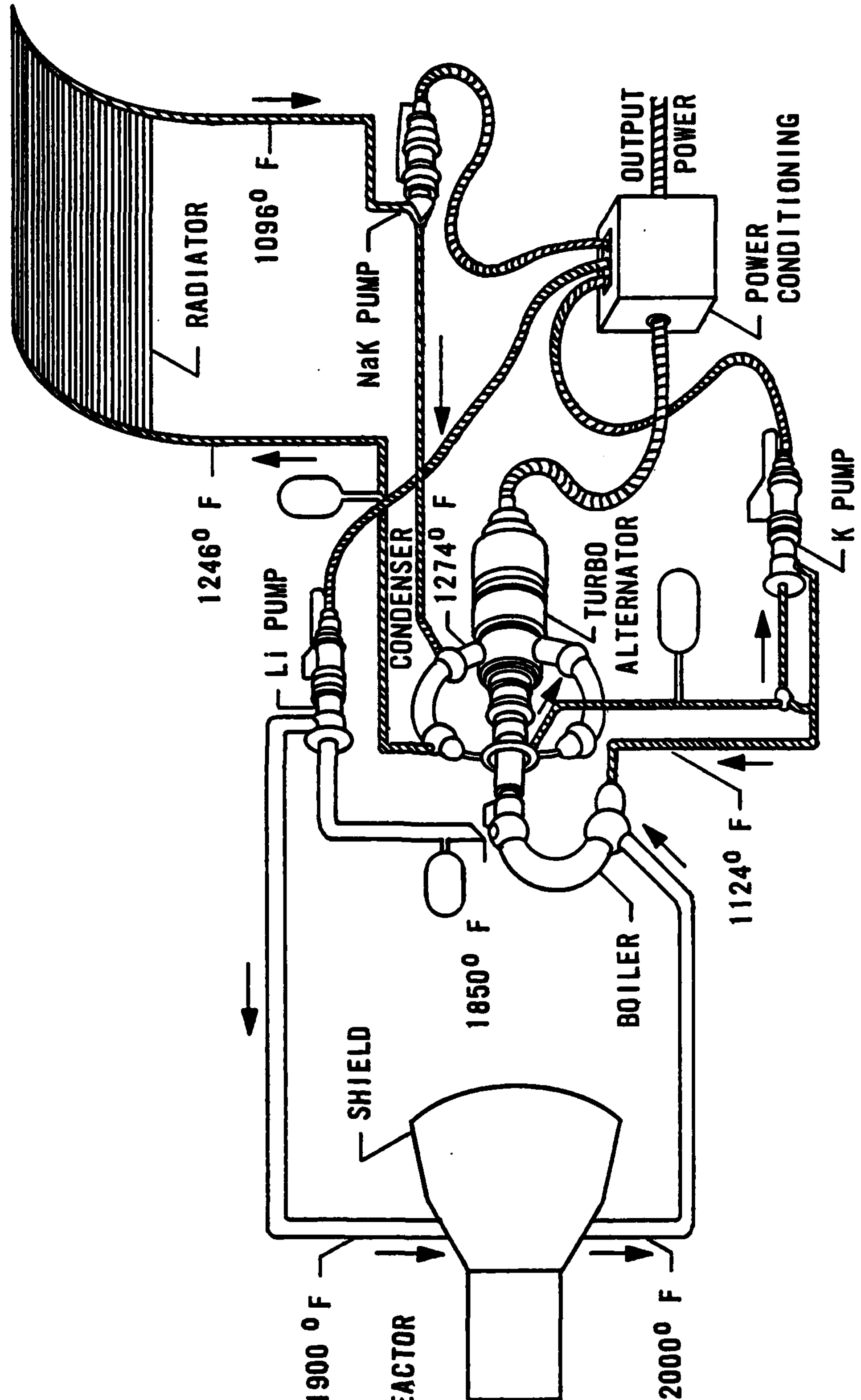

Figure 25. SNAP 50 schematic (after Ref. 60).

TABLE 9. WEIGHT BREAKDOWN OF THE SNAP 50 (after Ref. 61)

300 kWe	kg
Reactor	816.5
Primary System	199.6
Power Conversion System	775.6
Heat Rejection System	1106.2
Controls and Structures	419.6
Total Power Plant Wt	3397.4
Power Plant Specific Wt	11.34 kg/kWe

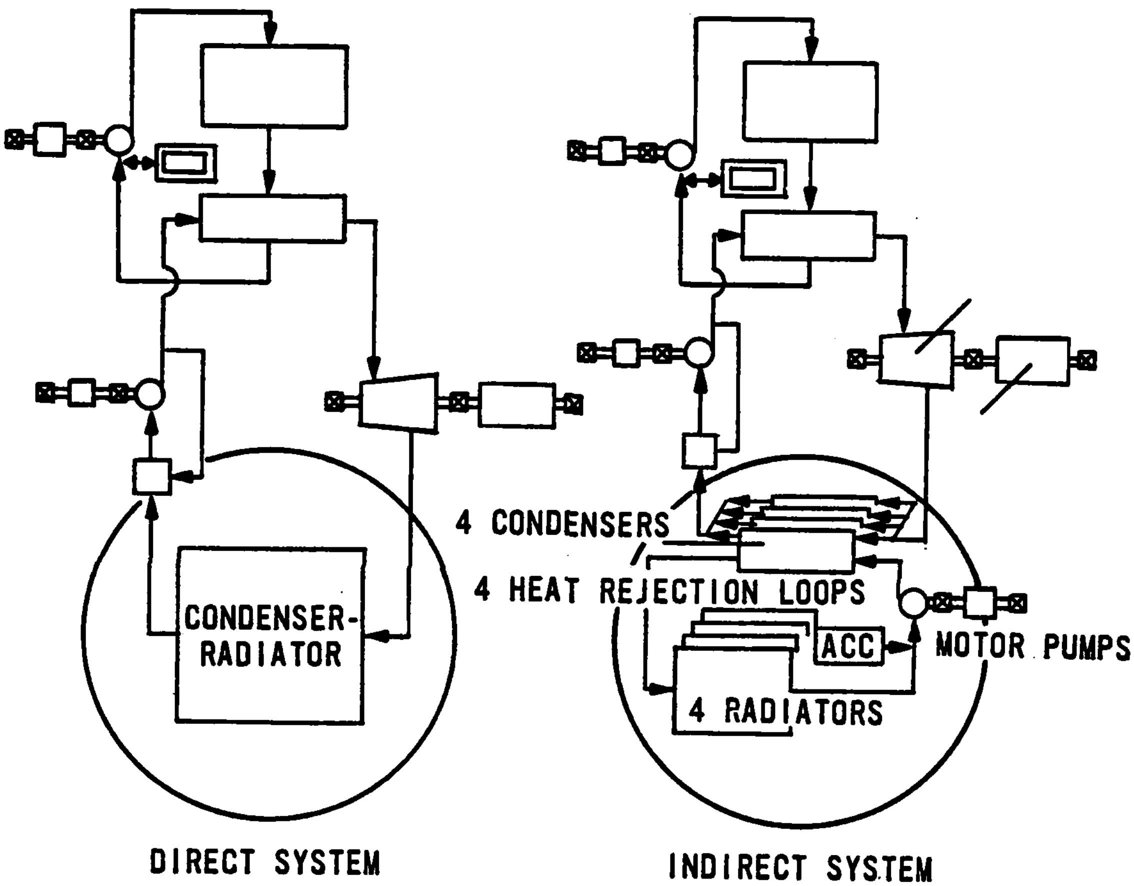

Figure 26. SNAP 50/SPUR power conversion system (after Ref. 60).

The following is an overview of the power conversion system planned for the SNAP 50. Heat is removed from the reactor and transported to the K boiler by molten Li. The Li is circulated through the reactor and over the boiler tubes by a high temperature pump. The Li from the reactor was delivered to the boiler at a temperature of 1093.3°C. Molten K from the boiler flows to the feed pump and then enters the boiler tubes where it is evaporated by the heat from the circulating Li. Potassium vapor from the boiler drives a turbine to which the alternator is coupled and the vapor exhausted from the turbine discharges into the tubes of an extended surface radiator at a temperature in excess of 537°C. The vapor was condensed in the radiator tubes from which the heat of condensation was radiated to space. The liquid K condensate from the radiator was then returned to the boiler feed pump by means of a jet pump.

Some of the electric power from the alternator was diverted and conditioned to operate the pumps, controls and other auxiliaries. The remainder of the alternator electrical output was delivered to the useful load via whatever power conditioning equipment may be required.

The entire system, with the exception of the electrical components, the radiator fins and armor, and a few special parts, was to be constructed of Cb-1 Zr alloy. The Cb-1 Zr is highly resistant to corrosion by Li. Extensive testing was completed on the Cb-1 Zr alloy, such as structural tests, corrosion tests and fuel irradiation tests.

RADIATOR

The space radiator used stainless steel meteoroid armor and stainless steel clad copper fins to increase the radiator surface area. Beryllium was also under consideration for the armor and fins (Ref. 61).

CONCLUSION

The SNAP 50 was a developmental reactor program separate from the main program at AI. The other SNAP reactors incorporated a thermal reactor with either thermoelectric or Rankine cycle energy conversion systems, whereas the SNAP 50 concentrated on a fast reactor with a K, Rankine cycle power conversion system. The SNAP 50 was advantageous in that it would operate a high conversion efficiencies and high power levels. But, because of the Rankine cycle conversion, it had a higher probability of single point failure and increased weight. Also, it operated at high temperature levels and material problems had to be taken into account.

Although the SNAP 50 program never went beyond the developmental stage due to a complete cut in funding, it was considered a feasible system for power levels of 300 to 1000 kWe. A complete, in-depth look into the SNAP 50 design and development can be found in Reference 22.

XII. LESSONS LEARNED

CONCLUSIONS

The SNAP reactor program was the beginning of the development of compact nuclear reactor systems for space applications in the United States. During the period from 1951 to 1973 a total of six prototype reactors were tested. The SNAP program opened the frontier for the development of compact nuclear reactors capable of producing high power levels at a small specific weight.

In the early fifties, when a projected need for space power was recognized, a pre-established mission was not identified. There were many envisioned missions which would require power levels a reactor system could provide, but many of these missions changed, were dropped or their power needs were met by other means. With the advancement of solar technology, the thrust for reactor technology development lessened. Also, many of the missions had different lead times which was not conducive in mating the power source with the mission.

There were many different missions identified for the SNAP 8 reactor, such as a manned space station, radar systems, reconnaissance systems, meterorological satellite, terrestrial power plant, lunar base power source, communication satellite and the Manned Orbiting Laboratory (MOL). Many of these systems were eventually developed but an alternate power source was used. During the late 1960s the SNAP 8 was considered essential for meeting the low power requirements for space. The time testing was completed on the S8DR and cracking of the fuel cladding was discovered coinciding with government cuts of the space power program. The loss in confidence in the SNAP 8 system extended into the whole program.

In identifying potential missions two questions should be asked: (a) Can an alternative source of energy meet these needs more efficiently, effectively and safely? and, (b) Is it honestly a realistic need, or will the program be scrapped within a few years time? The power need must be real! It is important to have a well defined goal and mission. If an advance reactor system is being developed without a clear cut purpose, the program will eventually be reduced or eliminated. At the start of the program it cannot be assumed that an indisputable need will appear down the road, rather it should be established clearly beforehand.

The SNAP program was coordinated by the AEC. The AF and NASA both played a part in funding and development but the overall coordinator was the AEC. This was advantageous in that the AEC was able to keep the program funded even during the times general support was lagging. Also, the reactor program had strong support by the JCAE. This program was considered to be a priority.

In 1963 the USAF pulled out all funding for the development and manufacturing of the Agena vehicle which was to be used to launch the SNAP 2 and SNAP 10A. Also, all AF funding on the SNAP 10A flight test was also withdrawn for lack of a minimum requirement for space nuclear power systems. Without the backing of the AF, the Bureau of the Budget took the position that specific mission requirements should govern the pace of the AEC's space reactor program (Ref. 52). The SNAP 2 reactor program, SNAP 50 program and SNAP 10A flight test were all cancelled due to a reorganization of priorities. But the AEC was able to appropriate the funding from within the department to proceed with the actual flight testing of the SNAP 10A.

The establishment of a strong central agency is an important consideration. It needs to be politically strong, capable of bearing through changes in the political network. Also, this agency can help to establish reasonable goals and follow them, to determine which missions are applicable and probable, to choose a feasible reactor design capable of meeting the goals and to coordinate the funding from several agencies to ensure a well coordinated and productive program.

The importance of a strong, central agency can be seen. Without the continued support of the AEC, the SNAP 10A would not have been flight tested. The AEC continued to support the reactor program even through a political lull.

Once a mission is identified it is important to establish early into the program the power needs, weight and size limits, and mode of operation. Will the system be pulsed or run at steady state? What is the maximum weight that can be put into orbit? Is the power need the absolute minimum or the ceiling? These questions need to be addressed early into the game.

The SNAP 50 was designed to operate at power levels from 300 to 1000 kWe. Four years of design, materials testing, and small scale system testing was completed with a budget of greater than $20 million per year. It was not until

the initial developmental program was completed and large scale testing was to begin that it was decided that the SNAP 50 power levels were too high for predicted mission needs. When programs were cut due to reorientation of priorities the advanced system was one of the first to be cut. The lead time for both the application and the reactor system should be addressed. The power needs should be established before the program begins to help ensure a strong and continuing program.

Safety will play a big role in determining the fate of the reactor program. If the reactor can never be launched due to the safety hazards, the program will be considered a waste. Therefore, a safety criteria should be established early on which will identify requirements which must be met. From here a safety plan can be established which would outline needed research and testing. An independent safety analysis program should be maintained to increase the level of confidence in the safety results and analysis. One thing that should be kept in mind is that a reactor will need to be launched as a proof-of-concept test. Before a user will risk their project, they will demand proof that the reactor is safe and reliable.

Areas of interest encountered in the SNAP 10A orbital test also should be taken into account. They include modeling of the launch stress load, the use of a heat shield during prestart-up of the reactor to ensure that the sodium-potassium would not freeze causing blockage in the system, the torque experienced by the spacecraft from the interaction of the thermoelectric pump magnet and converter current with the earth's magnetic field, the effect of solar heating on the system's power capabilities which cause a decrease in the temperature difference between the radiator and space, the effective neutron source level in space, to determine the effectiveness of the LiH radiation shield in space without the added scattering from test cell structures, and the change in performance of the thermoelectrics in space.

As stated earlier, there are several issues that must be addressed to ensure a strong reactor program. First, have an indisputable need which will help to ensure political support and funding. Second, initiate a strong control agency with enough clout to help ensure continuous support. Third, establish goals and design requirements early into the program so that the final designs can meet

the program needs. And finally, investigate the early research efforts which may open new avenues of thought and identify potential road blocks. Political, financial, developmental, and design problems have all been faced once in the pursuit of developing a space nuclear reactor. In understanding these problems, efforts can be made to prevent them from recurring in current and future space programs.

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